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TESTS OF BOND BETWEEN CONCRETE AND STEEL

BY

DUFF A. ABRAMS

BULLETIN No. 71

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ENGINEERING EXPERIMENT STATION

BULLETIN NO. 71 DECEMBER, 1913

TESTS OF BOND BETWEEN CONCRETE AND STEEL

BY DUFF A. ABRAMS, ASSOCIATE IN THEORETICAL AND APPLIED MECHANICS

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TESTS OF BOND BETWEEN CONCRETE AND STEEL

I. Introduction.

1. *Preliminary.*—The usefulness of reinforced concrete as a structural material depends on the strength and permanency of the bond between the concrete and the reinforcing metal, and for this reason bond resistance has received much attention from engineers and experimenters. It is said that Thaddeus Hyatt made tests to determine the bond between concrete and iron bars as early as 1876. During the past decade numerous bond tests have been reported. These tests have been characterized by a lack of uniformity in the form of the test specimen and in the methods of conducting the tests, as well as by the wide variations in the values reported for bond resistance. In nearly all the tests thus far published values of maximum bond resistance only have been given. These test results and the discussions called forth by them have furnished the basis for a great variety of opinions as to the value of bond resistance. Many explanations of the source and nature of bond resistance have been given. Various methods have been advocated for increasing bond resistance and numerous devices have been employed for this purpose.

Present American practice is fairly standardized as to the bond stresses to be used in designing, but a rational basis for the stresses used is lacking and there is a great diversity of practice in the methods of calculating these stresses. There are many phases of bond action which are not now understood. It is evident that the distribution of bond stress in reinforced concrete members under load and the nature and value of bond resistance under given conditions may well be the subject of experimental investigation.

2. *Scope of Bulletin.*—The tests reported in this bulletin were undertaken with a view to securing additional information on the nature of the bond resistance of reinforcing bars in concrete, to determining values of bond resistance for a wide range of conditions, and to studying bond

action in specimens of different forms. Tests were made on pull-out specimens and on reinforced concrete beams. In both forms of specimen attention was given to obtaining accurate measurement of the slip of bar through the concrete as the loading progressed. In many of the beam tests the slip of bar at various points along its length was measured for different loads. In the discussion of bond resistance the load-slip-of-bar relation has been utilized to a considerable extent. These measurements are useful in indicating the distribution of bond stress. They are particularly significant in the beam tests. In a few of the beam tests the distribution of bond stress was studied by measuring the changes in the stress in the longitudinal reinforcement throughout the length. The values found for bond resistance and the relative bond resistance found in beam tests and pull-out specimens are also interesting features of the investigation.

The pull-out tests consisted in applying load to a short reinforcing bar embedded in a block of concrete. The concrete block was generally 8 in. in diameter and 8 in. long, with the bar embedded axially. In certain groups of tests these dimensions were varied. The size of bar used varied between $\frac{1}{4}$ in. and $1\frac{1}{4}$ in. The pull-out tests covered a wide range and included effect of dimensions of specimen, effect of form of bar, effect of conditions of storage, effect of age and mix, using both plain and deformed bars, effect of different methods of loading, bond resistance of concrete setting under pressure, effect of reapplied loads, comparison with the bond resistance of reinforced concrete beams, etc. The deformed bars used included most of the forms in use at the time the work was begun, but it should be noted that the tests with deformed bars were intended to bring out the action of the deformed bar as contrasted with the plain bar and not to determine the value of particular forms of bars.

A special effort was made to determine the behavior of beams subjected to high bond stresses. The beams tested were 8 by 12 in. in section with an effective depth of 10 in. The span length was generally 6 ft.; a few beams were tested with span lengths of 5 to 10 ft. All beams were tested with two symmetrical loads, generally at the one-third points of the span. With the exception of six tests, the longitudinal reinforcement consisted of a single bar of large diameter placed horizontally throughout the length of the beam. Both plain and deformed bars were used.

3. *Acknowledgment.*—The tests reported herein were made in the Laboratory of Applied Mechanics of the University of Illinois and formed a part of the investigations of reinforced concrete and other structural materials which are being conducted by the Illinois Engineering Experiment Station. These tests cover the experiments which were designed with special reference to a study of bond between concrete and steel during the period 1909-1912. The work was done under the direction of A. N. Talbot, Professor in Charge of the Department of Theoretical and Applied Mechanics. The writer is indebted to Professor Talbot for many helpful suggestions in planning the tests and in interpreting the data.

In the 1912 beam series the work of testing was done under the writer's supervision by Messrs. W. W. Manspeaker and A. W. Wand, senior civil engineering students of the class of 1912. These tests furnished the subject-matter of their baccalaureate thesis, where a very creditable report on the tests was presented. These men exercised great care in carrying out the routine of the work and they are to be commended for the way in which they met the demands of an unusually arduous program of tests. The other tests were made by the writer with the assistance of various members of the Laboratory staff.

II. Materials, Test Pieces and Methods of Testing.

4. *Concrete Materials.*—The materials were the same as used for other concrete and reinforced concrete specimens made and tested by the Engineering Experiment Station during the period 1909 to 1912. The quality of the materials may be considered as representative of that used in first-class concrete work in the central states.

Cement. Most of the test specimens were made with Universal portland cement, which was furnished by the manufacturers. Chicago AA portland cement was used in the 1909 series of beam tests and in Batch No. 4 of the 1909 pull-out tests. Lehigh cement was used in part of the 1911 beam series. The Chicago AA and Lehigh cements were purchased from a local dealer. The results of briquette tests of these cements are given in Table 1. Samples were taken at intervals throughout the season. Each value given is the average of five briquette tests. Vicat needle tests on the three samples of the 1909 lot of Universal cement showed initial set to occur at 1 hr. 45 m., and final set at 3 hr. 45 m. after mixing. Sieve analysis showed 96.5% passing a No. 100 sieve and 81.9% passing a No. 200 sieve. The 1912 lot of Universal cement (7 samples) gave the following average values: initial set, 3 hr. 5 m., final set, 6 hr. 32 m.; 97.2% passing a No. 100 sieve and 81.8% passing a No. 200 sieve. All cement tests recorded in this bulletin were made by Mr. B. L. Bowling, Assistant in Charge of Cement Laboratory, University of Illinois.

TABLE 1.

Briquette Tests of Cements.

Each value is the average of five tests.
Unless otherwise noted, standard Ottawa sand was used in the 1–3 briquettes.
The results are expressed in pounds per square inch.

Sample No.	Neat		1–3		Neat		1–3	
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
	Universal Cement		(1909)		Chicago AA Cement.			
1	607	732	197	281	742	783	205	270
2	595	772	179	280	716	807	232	306
							288*	331*
3	617	853	160	278	725	768	176	254
Average	606	786	179	280	728	786	204	277
	Universal Cement		(1911)		Lehigh Cement.			
1	589	674	198	278	719	805	248	329
			265*	323*				
2	684	709	227	283				
3	653	731	240	319				
4	662	696	214	282				
Average	647	702	220	290				
	Universal Cement		(1912)					
1	585	685	239	315				
2	577	694	225	297				
3	691	715	242	306				
4	617	792	231	326				
5	588	672	246	333				
6	612	758	253	323				
7	698	884	287	372				
Average	624	743	246	325				

*** Made with sand used in making concrete; not included in average.**

Sand. The sand came from a deposit of glacial drift near the Wabash River at Attica, Indiana. Nearly all the clay or loam had been removed by washing. Fineness tests of samples from the three lots of sand are given in Table 2. A single set of briquette tests made from a sample of the 1909 lot of this sand, using Chicago AA cement, gave values about 10% higher than briquettes made from the same sample of cement using standard Ottawa sand. A set of briquettes made from the 1911 sand using Universal cement gave values about 25% higher than the standard sand. The values from these tests are included in Table 1. The sand was well graded, but it will be noted that the 1912 sand was somewhat coarser than the other lots.

Stone. The crushed limestone came from Kankakee, Illinois. It had been screened through a 1-in. screen and over a ¼-in. screen. Mechanical analyses of a number of samples of this stone are given in Table 3. It contained about 48% voids.

5. *Concrete.*—The concrete was proportioned by loose volume. The material was weighed also in order to obtain an independent check on the proportions of each batch. The ratios of the weights of the materials used in most of the specimens are given in Tables 4, 25, 27 and 31. In making the 1909 specimens the cement was measured in buckets, as was done for the other materials. This resulted in considerable variation in the batches. The practice of considering 95 lb. of cement equal to 1 cu. ft. was adopted for the 1911 and 1912 tests. This is in reality a weight proportioning for the cement and is more rational than the older method.

The work of mixing and placing the concrete was done by men of considerable experience in concrete work. The foreman has been employed in the laboratory since 1905, but has spent five or six months each year on contract work in concrete. All of the concrete except that used in the last two-thirds of the 1912 beam series was mixed by hand. The hand-mixing was done directly on the floor of the concrete laboratory. The cement and sand were first mixed dry; the stone, which had previously been thoroughly moistened, was added and the batch then turned until it presented a uniform appearance. The first operation usually required five or six turnings, and the last two or three. Water was added and the material then turned until thoroughly mixed.

In December, 1911, a 9-cu. ft., motor-driven, batch-mixer, made by the Marsh-Capron Mfg. Co., Chicago, Illinois, was installed. The second and third beams in each set of three in the 1912 series and the corresponding auxiliary specimens, as well as some later miscellaneous pull-out specimens, were made of machine-mixed concrete. With the machine running continuously, the stone and sand were placed in the mixer and about one-half the required amount of water admitted. The cement was then added and the remainder of the water admitted at the same time. The amount of water used in each batch was measured and recorded. The drum of the mixer operated at about 22 revolutions per minute. Each batch was mixed for about 5 minutes after adding the cement. When the mixing was complete, the batch was dis-

TABLE 2.

MECHANICAL ANALYSIS OF SAND.

Sieve No.	Separation Size inches	Per cent Passing Each Sieve		
		1909	1911	1912
3	0.28	99.7	99.8	100.0
5	.174	95.9	96 7	88.0
10	.091	77.5	74.4	54.3
12	.067	70.3	67.6	47.5
16	....	62.8	61.0	41.7
18	.043	51.1	50.2	32.9
30	.027	28.2	30.3	21.2
40	.019	16.9	17.0	13.3
50	.013	5.8	7.0	5.1
74	.009	3.1	3.3	2.7
150	....	0.8	0.8	1.0

TABLE 3.

MECHANICAL ANALYSIS OF STONE.

Size of Square Opening	Separation Size inches	Per cent Passing Each Sieve		
		1909 22 Samples	1911 8 Samples	1912 5 Samples
1 in.	......	100	100	100
¾ in.	......	87	95	95
½ in.	......	46	57	67
⅜ in.	......	29	32	46
No. 3	0.280	14	18	26
No. 5	.174	2	3	8
No. 10	.091	1	2	3

charged onto the concrete floor, and was later removed to the forms directly with shovels or by means of a wheelbarrow. The concrete was mixed rather wet so that very little ramming was necessary after placing it in the forms.

6. *Reinforcing Steel.*—The plain round bars of ¾-in. diameter and larger sizes used in the 1909 and 1911 tests were of high-carbon steel. The smaller sizes of plain round bars used in a few of the pull-out specimens and all the plain bars used in the 1912 series were of mild steel. The corrugated bars and most of the other types of deformed bars used were of high-carbon steel. The Thacher bars were of mild steel. See Table 13 and Fig. 21 for details of deformed bars. Additional notes concerning the character and preparation of the steel are given with the discussion of the various groups of tests.

Tensile tests on the steel are not given in this bulletin. In only a few of the tests was the steel stressed to the yield point, and these are noted in the tables.

7. *Pull-out Specimens.*—The specimens for pull-out tests consisted of a cylindrical block of concrete with a steel bar embedded axially. The blocks were generally 8 in. in diameter with embedment of 8 in. In some of the tests both the diameter of the block and length of embedment varied from these figures. The pull-out specimens were usually cast in a vertical position with the bar projecting about 16 in. below and ¼ in. above the finished block. The forms, consisting of galvanized sheet-steel, were set up on a platform made of two 8-in. or 12-in. I-beams placed with their flanges about 2 in. apart. A planed cast-iron base plate made the bottom of the form for the concrete cylinder. A central hole in the base plate allowed the rod to pass through. These plates were removed when the specimens were taken from the forms. The specimens were tested in the same position, the load being applied to the longer end of the bar. The usual form of pull-out specimen is shown in Fig. 1 (a). Other pull-out specimens of unusual form are shown in Figs. 36, 41 and 42.

Nearly all of the pull-out specimens with deformed bars in the 1909 series and certain other groups of specimens were reinforced against bursting by means of six or seven turns of ¼-in. wire in the form of a spiral. This spiral was set inside the form before placing the concrete and was near the outer surface of the concrete block; see Fig. 1 (b). In general, the spiral reinforcement was not used in the pull-out specimens made with the reinforced concrete beams.

Generally, the test pieces were made in sets of five; but for a few of the tests the specimens were made in sets of two to ten. The pull-out specimens made as companion pieces to the 1911 and 1912 series of beams were made in sets of three. When practicable, the individual specimens of a set in the 1909 pull-out series were made from different batches, thus minimizing accidental effects in a given set. Frequent duplicate sets were made in order that comparison might be made

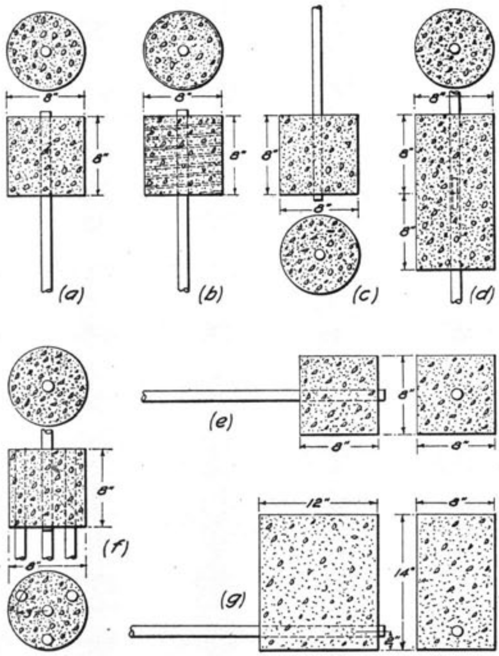


FIG. 1. TYPES OF PULL-OUT SPECIMENS USED IN THE TESTS.

between concretes from different batches. The numbers of the batches from which the pull-out specimens of the 1909 series were made are given with the tables of test data.

In the group of tests on deformed bars (Table 14) one specimen of each set was made from each of five batches which were mixed at intervals of about two weeks. In the series on "Effect of Age and Mix," (Table 16) three specimens with plain round bars and two with corrugated bars for each age were made from one batch, and the remaining specimens from a second batch.

8. *Reinforced Concrete Beams.*—The 1909 series of tests included 11 reinforced concrete beams; the 1911 series, 36 beams, and the 1912 series, 63 beams. All of the beams (with the exceptions mentioned in Table 27) were 8 by 12 in. in section. The length was generally 6½ ft. A few of the beams in the 1911 and 1912 series were made in lengths of 5½, 7½, 8½ and 10½ ft. The arrangement of the reinforcement for typical forms of beams is indicated in Fig. 2. The ends of the bars were squared, and extended flush with the ends of the beam. In all but two sets of beams the longitudinal reinforcement consisted of a single straight bar placed in the middle of the width of the beam, with its center 10 in. below the top. One set of three beams in the 1912 series was reinforced with 3 ¾-in. rounds and one set with 4 ⅝-in. rounds.

All of the beams, except a part of the 1911 series, were reinforced with vertical stirrups of plain round bars in sizes varying from ¼ to ⅝ in. The stirrups engaged the longitudinal reinforcement and extended to the top surface of the beams; they were placed 4 in. apart throughout the outer thirds of the beam in the 1909 series and 6 in. apart in other beams in which stirrups were used. In the beams in which the longitudinal reinforcement consisted of a single bar, the stirrups were V-shaped; in the beams in which three or four smaller rods were used for longitudinal reinforcement, the stirrups were U-shaped; in the 1911 and 1912 beams the ends of the stirrups were curved inward.

The beams were made in wooden forms directly on the concrete floor of the laboratory, a sheet of building paper having been placed under the form. Generally enough concrete was mixed at one time to make two beams and the corresponding auxiliary specimens. Enough concrete was placed in the form at first to fill it a little above the point where the center of the reinforcing bar should be. After placing the reinforcing steel in position, the form was filled in layers of about 3 in. depth. From the first few batches of machine-mixed concrete only one beam was made; later it became the practice to discharge two batches together on the cement floor of the laboratory before commencing the making of the beams. This supplied enough concrete for two or three beams and the corresponding auxiliary specimens.

The 1909 beams were considered a preliminary group. The beams of the 1911 and 1912 series were generally made and tested in sets of three.

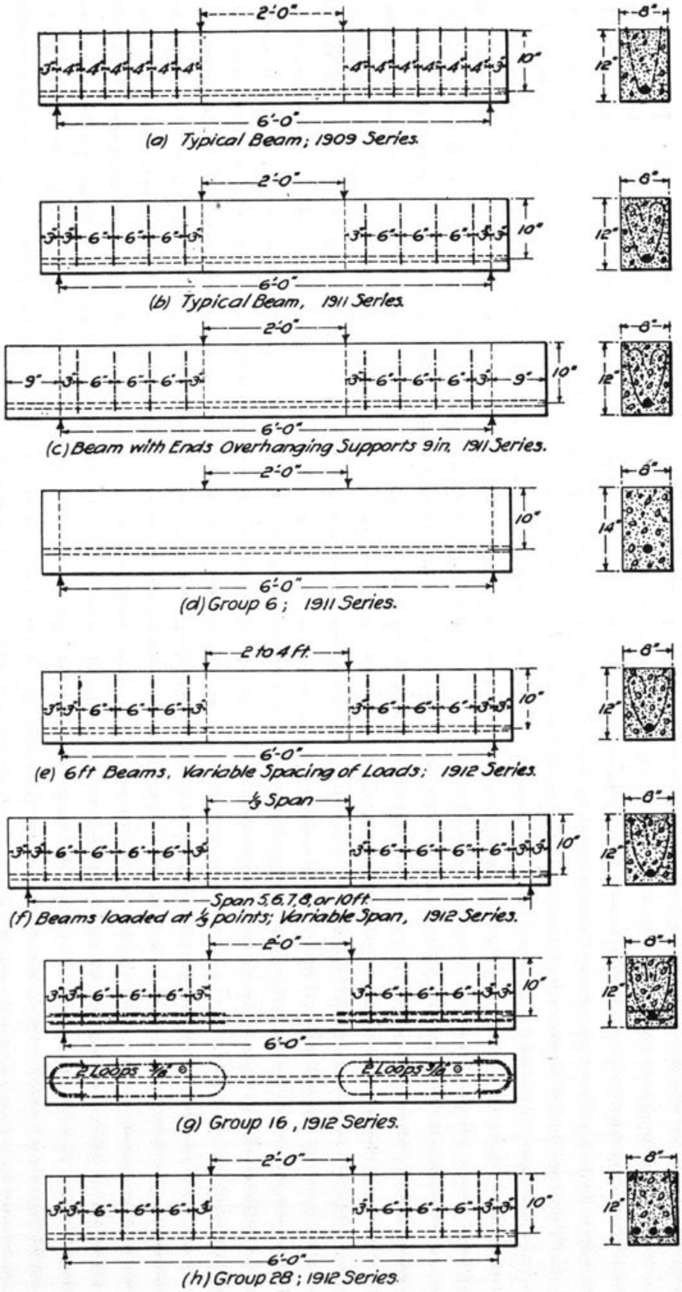


FIG. 2. TYPICAL FORMS OF REINFORCED CONCRETE BEAMS USED IN THE TESTS.

9. *Auxiliary Test Specimens.*—From each batch of concrete three or more 6-in. cubes were made for compression tests. With several groups of the 1909 pull-out specimens in which the age at test or condition of storage were varied, sets of cubes were made for each variation. The 6-in. cubes were made in metal forms. Plain concrete beams 6 by 8 in. in section and 42 in. long, for flexure tests, were made from each batch of the 1909 pull-out tests. Pull-out specimens were made from the same material as was used in many of the reinforced concrete beams of the 1911 and 1912 series.

10. *Storage of Concrete Specimens.*—The 1909 pull-out specimens and the corresponding 6-in. cubes were stored in damp sand unless otherwise noted. The plain concrete flexure beams were stored in open air. These forms were removed after four days except for the specimens tested at age of two days. The specimens were stored in a damp room where the temperature range was about 65° to 75° F.

All of the reinforced concrete beams were stored in the open air of a room in which the temperature varied from 50° to 75° F. They were wet daily with water from a hose until about two months old. The pull-out specimens made with the 1911 and 1912 series of beams were stored under the same conditions as the beams. The 6-in. cubes made with the beams were stored in damp sand. The forms of the beams and their auxiliary specimens remained in place seven days.

The variations in the conditions of storage of the pull-out specimens made at different times should be borne in mind when comparing the bond stresses developed in the different series of tests.

The 1909 pull-out specimens were made between Jan. 1 and May 5; the 1909 beams between Feb. 1 and April 15; the 1911 series of beams between Jan. 1 and April 15; and the 1912 series of beams between Nov. 1, 1911, and Jan. 22, 1912. Other smaller groups included under "Miscellaneous Tests" were made during the season 1911-1912. The 1909 pull-out tests were generally made at age of about 60 days. In a few of the groups of pull-out tests the age ranged from 2 days to about 3½ years. The 1909 beams were tested at about 100 days; the 1911 beams and pull-out tests at about 8 months; the 1912 beams and companion specimens at about 60 days.

11. *Method of Making Pull-out Tests.*—In testing, the pull-out specimen was placed above the weighing head of the testing machine as shown in Fig. 3. The lower end of the embedded bar was engaged by the grips of the pulling head of the testing machine, the load being

transmitted from the concrete cylinder which rested on a planed cast-iron base plate, through a rubber cushion to a spherical bearing block through which it passed to the weighing head of the machine. The rubber cushion served to reduce the rate of application of the load during the earlier stages of the tests and to minimize the effect of shocks arising from the slipping of the grips or vibration of the testing

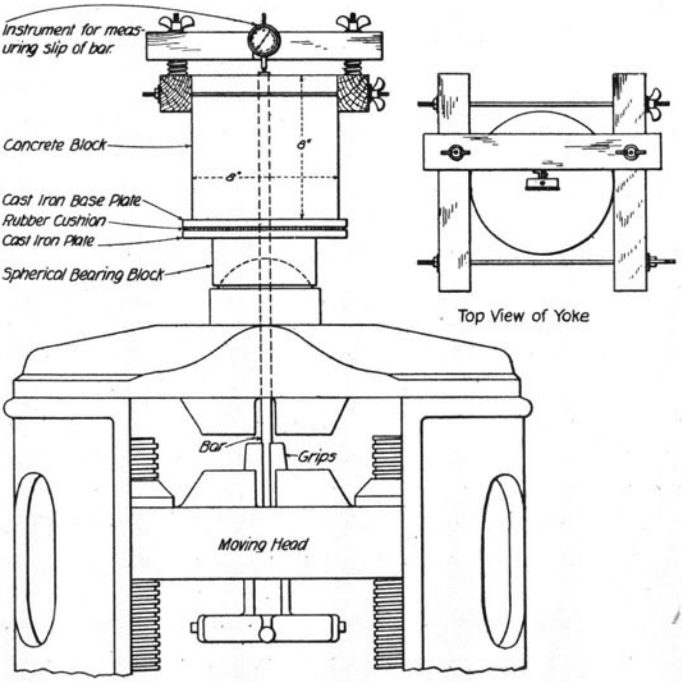


FIG. 3. PULL-OUT SPECIMEN IN MACHINE READY FOR TEST.

machine. The spherical bearing block allowed the bar to take a vertical position and tended to prevent bending action due to the bar being non-central in the machine or not parallel to the axis of the cylinder.

A 100,000-lb. Riehle testing machine was used for all the pull-out tests. In these tests the moving head of the testing machine moved at the rate of 0.05 in. per minute.

In the pull-out tests the amount of movement of the free end of the embedded bar was measured by means of an Ames gage in contact with the upper or free end of the bar. The instrument was mounted on a yoke which was attached near the top of the concrete cylinder, as shown in Fig. 3. This instrument is self-indicating and requires no manipulation during the test. It is graduated directly to 0.001 in., and fractional parts of a division may readily be estimated. In order to test the stability of the yoke and to determine whether the top face of the cylinder remains a plane section during the test, four additional Ames gages were attached to the yoke at different points along the diameter of the cylinder in a number of tests. The yoke remained perfectly stable. The concrete ¼ in. from the bar showed a measurable depression, about 0.0002 in. at loads near the maximum, but no depression could be measured at points further than 1 in. from the edge of the bar.

The load was applied continuously, except in a few of the tests in which the load was released and reapplied after the beginning of slip at the free end of the bar. As the test progressed the loads on the testing machine corresponding to an end slip of 0.0005 in., 0.001, 0.002, 0.005, 0.01, 0.02, 0.05, and 0.10 in., were noted. A slip of 0.0005 in. is about the smallest amount that should be used in making comparison, although smaller amounts can readily be measured.

Two men were required to conduct a test; one man operated the testing machine and observed the loads, while the other observed the amount of movement of the bar and kept the test notes.

12. *Method of Making Beam Tests.*—The reinforced concrete beams were loaded in a 200 000-lb. Olsen testing machine. The beams were tested under two equal loads applied generally at the one-third points of the span length; exceptions to this method of loading are noted in the tables. In general the ends of the beams overhung the supports 3 in.; in some of the 1911 tests the overhang was 9 and 15 in., respectively. The supports consisted of roller or rocker bearings. Rollers were used also to transmit the load to the top of the beams. Fig. 56 shows a beam set up in the testing machine ready for loading.

Center deflections and the movement of the ends of the reinforcing bars were measured by means of Ames gages. For measuring deflections the Ames gage was attached at the middle of a wooden bar which was carried by metal points at the mid-depth of one face of the beam at points directly over the supports. A small metal bracket attached to the beam at mid-span, transmitted the movement of the beam to the gage. For measuring the movement of the ends of the reinforcing bar, the gages were carried by yokes in such a way that the plunger had a direct bearing against the end of the bar.

In many beams of the 1911 and 1912 series observations were made on the amount of movement of the reinforcing bar with respect to the adjacent concrete at several points along the length of the beam as described in Art. 66. The method of attaching the instruments to the beam is shown in Fig. 56.

The load was applied in increments of 1000 or 2000 lb. In all but five of the beam tests the load was increased progressively to failure.

13. *Auxiliary Tests.*—The 6-in. cubes were tested for compressive strength only. About one day before testing, the faces to be loaded were bedded in a thin layer of plaster of paris. At least one set of three cubes made with each batch of the 1909 pull-out specimens was tested at age of 60 days.

The 6 by 8 in. plain concrete beams made with the 1909 pull-out specimens were loaded at the one-third points of a 3-ft. span with the 8-in. dimension vertical. The age at test was generally 60 days.

III. Experimental Data and Discussion.

14. *Preliminary Discussion of the Nature of Bond Resistance.*—In this preliminary discussion it will be necessary to anticipate certain conclusions which appear in the following pages. The tests therein reported indicate that if a bar embedded in concrete is subjected to a tensile stress sufficient to overcome the bond resistance and withdraw the bar, certain definite relations exist between the amount of movement of the bar and the bond stresses developed. In the case of plain bars of ordinary mill surface there is no appreciable movement of the bar until a bond stress about 60% of the maximum bond resistance has been developed. If the bar is further stressed until the slip amounts to, say, 0.1 in. it will be seen that the bond-slip relations have undergone numerous changes. After slipping begins, the bond stress increases with further movement of the bar, very rapidly at first, then more slowly until the maximum bond resistance is reached. After the maximum bond resistance is reached, the bond stress drops off with further slip and at a slip of, say, 0.1 in. amounts to about 50 to 60% of the maximum.

For purposes of this discussion bond resistance may be divided into two elements which we shall designate as (1) adhesive resistance and (2) sliding resistance. The term adhesive resistance is used to designate the bond resistance developed before movement of bar with respect to the adjacent concrete begins. Sliding resistance is applied to the resistance developed as a result of the movement of the bar. Adhesive resistance may be considered as due to tangential adhesion between the concrete and steel and to static friction. The origin of tangential adhesion is not well understood, but its presence is a matter of universal experience with materials of the nature of mortar and concrete. It is recognized that tangential adhesion does not account for all the resistance developed before slipping begins, but the difference may be attributed to static friction developed by the pressure or grip of the concrete on the bar. As soon as the adhesive resistance is overcome, that is, as soon as the bond stress exceeds the sum of the tangential adhesion plus the static friction, there is a movement of the bar with respect to the adjacent concrete. Although we cannot accurately divide this adhesive resistance into its component elements, the sum of these elements or the total adhesive resistance can be determined, and it is found that under certain conditions it bears a definite ratio to the ultimate bond resistance.

The bond resistance which is developed after slip of bar begins may be said to be due entirely to sliding resistance. Friction between bodies in contact arises primarily from roughnesses of their surfaces; its value is expressed as the product of the coefficient of friction into the normal pressure which exists at the surfaces of contact. The static friction mentioned above is due to the same cause. The roughness of surface in the case of a bar embedded in concrete is due to inequalities in the surfaces of contact which arise from irregularities of section and alignment of the bar and the corresponding conformation of the concrete. The coefficient of friction between concrete and steel for the conditions present in these tests has not been determined. The normal pressure at the surface of the bar may be due to the following causes: (a) initial stresses generated by shrinkage of the concrete during setting and hardening; (b) wedging of the bar in the concrete following a movement from its original position. This wedging is caused by the inequalities in the bar mentioned above and in itself will give an added resistance. Apparently it is augmented under certain conditions by concrete adhering to the bar.

In the above discussion the various components of bond resistance have been mentioned in the order in which they become effective in resisting bond stress. It is evident from these considerations that what has been termed adhesive resistance, that is, the amount of bond resistance which may be utilized before slipping begins, is by far the more significant element. While frictional resistance is of importance, reliance should not be placed on this element of bond resistance.

It was stated above that we cannot accurately divide adhesive resistance into its component elements; however, certain tests do give some indication of the values of these components. A large number of specimens with polished round bars embedded 8 in. in 1-2-4 concrete tested at age of 60 days gave a maximum bond resistance of about 160 lb. per sq. in. In these tests frictional resistance (both static and sliding) was reduced to a minimum and bond resistance after slipping began was almost nil. We may conclude then that 160 lb. per sq. in. represents about what may be expected for the tangential adhesion between steel and concrete of this quality. It seems probable that the same value may be used for the tangential adhesion between any clean steel surface and concrete of the quality used. Round bars with ordinary mill surface tested under the same conditions as the polished bars show slip to begin at, say, 260 lb. per sq. in. with a maximum bond resistance of about 440 lb. per sq. in., developed after a slip of about 0.01 in. had occurred. The difference of about 100 lb. per sq. in. between the bond resistance developed by the polished bars and by the ordinary bars when slipping begins (corresponding also to the maximum for the polished bars) may be said to represent the value of static friction for the bars of ordinary mill surface above that of polished bars embedded in the same concrete. The additional bond resistance developed by the ordinary bars after slipping begins is due to frictional resistance.

The above observations refer primarily to the general case of bond between concrete and plain bars; for deformed bars, certain obvious modifications in these statements would be necessary. It will be seen later that the conditions under which the specimen is molded and tested have an important bearing on the bond resistance developed in any case.

In reinforced concrete beams, where the reinforcing bars are considered to take the main tensile stresses, the phenomena of bond action are complicated by the stiffness of the adjoining concrete in resisting stretching concurrently with the steel. This results in anti-stretch slip, a term which is discussed at length in Art. 68. The presence of this stress makes it desirable to distinguish between the phenomenon of anti-stretch slip and the slip produced by ordinary beam action.

15. *Strength of Concrete.*—The compressive and flexural strength of the various batches of concrete used in the 1909 series of pull-out specimens are given in Table 4. For convenience of reference a sum-

TABLE 4.

RECORD OF BATCHES OF CONCRETE USED IN THE 1909 PULL-OUT TESTS.

The average compressive strength of 69 6-in. cubes from 19 batches of 1-2-4 concrete is 2150 lb. per sq. in.; the average modulus of rupture of 18 6 by 8-in. plain concrete beams loaded at the ⅓ points of a 36-in. span, is 296 lb. per sq. in. The average values with the mean variations for the cube and plain beam tests may be expressed as 2150±58 and 296±16 lb. per sq. in. respectively.

The tests given in this table were made at age of about 60 days.

Stresses are given in pounds per square inch.

Batch No.	Date Made (1909)	Number of Specimens from Batch			Mixture by Loose Volume	Mixture by Weight	Compressive Strength of 6-in. Cubes	Modulus of Rupture of 6 x 8 x 36-in. Plain Beams
		Pull-out	6-in. Cubes	Flexure Beams				
1	Jan. 1	47	27	1	1-2-4	1-2.4-4.3	1815	376
2	Jan. 7	48	18	1	1-1½-3	1-1.8-3.3	3060	359
3	Jan. 12	25	15	1	1-2-4	1-2.5-4.0	2898	550
4°	Jan. 13	40	15	1	1-2-4	1-2.4-5.5	1913°	338°
5	Jan. 18	39	39	1	1-3-6	1-3.6-6.3	1908	282
6	Jan. 25	5	6	1	1-1-2	1-1.5-2.0	4061*	374
7	Jan. 22	5	6	1	1-4-8	1-5.0-8.8	1155*	151
8	Jan. 22	5	6	1	1-2-2	1-2.1-1.9	2696*	332
9	Jan. 22	5	6	1	1-5-10	1-6.3-10.2	533*	62
10	Jan. 27	43	6	1	1-2-4	1-2.4-4.2	2180*	255
11	Feb. 1	24	3	1	1-2-4	1-2.4-4.3	1840	375
12	Feb. 9	47	27	1	1-2-4	1-2.2-3.8	2637	303
13	Feb. 15	25	18	1	1-1½-3	1-1.9-3.3	2688	385
14	Feb. 15	5	3	1	1-2½-5	1-3.0-5.1	1555	223
15	Feb. 15	5	3	1	1-2-3	1-1.8-2.4	1733	302
16	Feb. 25	5	3	1	1-2-5	1-2.1-5.0	1685	122
17	Feb. 19	50	6	1	1-2-4	1-2.3-4.3	1683*	240
18	Feb. 25	5	3	1	1-2-1	1-2.1-1.1	2870	336
19	Feb. 25	30	21	1	1-3-6	1-3.4-6.2	1242	183
20	March 1	42	18	1	1-1-2	1-1.2-2.1	3000	367
21	March 6	45	21	1	1-4-8	1-4.6-8.3	1298	167
22	March 10	23	3	1	1-2-4	1-2.3-4.2	2043	213
23	March 11	33	18	1	1-1-2	1-1.2-2.0	3488	335
24	March 15	51	6	1	1-2-4	1-2.0-3.5	1468*	151
25	March 19	25	3	1	1-2-4	1-2.4-4.3	1950*	165
26	March 20	30	18	1	1-4-8	1-4.8-8.5	800	...
27	March 23	57	6	1	1-2-4	1-2.4-4.3	1675	247
28	March 30	5	3	1	1-2-6	1-2.4-6.6	1108	113
29	March 30	10	3	1	1-2-0	1-4.2-0.	....	357
30	March 27	53	6	1	1-2-4	1-2.4-4.2	1715	172
31	March 31	38	3	1	1-2-4	1-2.3-4.1	2300	332
32	March 31	5	3	1	1-2-8	1-2.4-8.0	1240	117
33	April 8	40	24	1	1-1½-3	1-1.6-3.1	....	371
34	April 19	42	3	1	1-2-4	1-2.5-4.5	1950	202
35	April 23	45	9	1	1-2-4	1-3.1-5.9	3040	427
36	April 16	26	3	1	1-2-4	1-2.4-4.5	1770	238
37	April 24	48	3	1	1-2-4	1-2.4-4.2	2460	357
38	May 5	7	3	1	1-3-6	1-3.7-6.5	967	257
39	April 29	60	21	1	1-2-4	1-2.2-4.1	2190	379
40	May 3	55	36	..	1-2-4	1-2.4-4.3	2560	...
Total		1198	444	39				

° Batch No. 4 was made from Chicago AA cement; all others from Universal cement.

* Average of 6 tests; all other values for cube strength are the averages of 3 tests.

mary of the strength of concrete from the most important groups of tests is given in Table 5. This table includes all the tests on 6-in. cubes which were stored in damp sand and tested at age of about 60 days. The average compressive strength of 69 6-in. cubes from 19 batches of 1-2-4 concrete in Table 4 is 2150 lb. per sq. in.; the average flexural strength of the same concrete, 296 lb. per sq. in. Values for the compressive strength of the concrete used in each group of specimens are given in the tables of test data. Other data of compressive strength for different mixes and ages are shown in Tables 16 and 18 and in Fig. 35. Values for different conditions of storage are given in Table 12.

TABLE 5.

Compressive and Flexural Strength of Concrete.

All cubes given in this table were stored in damp sand. The plain beams were stored in the open air.

Cube tests for other ages and conditions of storage are given in Tables 12 and 16. Stresses are given in pounds per square inch.

Mix	Cement	Method of Mixing	Number of Batches	Age at Test days	6 x 8 x 36-in. Plain Beams		6-in. Cubes	
					Number of Tests	Modulus of Rupture	Number of Tests	Compressive Strength
				1909				
1-1-2	Universal	Hand	3	61	3	362	12	3653
1-1½-3	Universal	Hand	3	62	3	338	6	2874
1-2-4	Universal	Hand	19*	64	18	296	69	2150
1-2½-5	Universal	Hand	1	61	1	223	3	1555
1-3-6	Universal	Hand	3	62	3	241	9	1372
1-4-8	Universal	Hand	3	60	2	159	12	1102
1-5-10	Universal	Hand	1	60	1	62	6	533
1-2-0	Universal	Hand	1	72	1	357	..	....
1-2-1	Universal	Hand	1	60	1	336	3	2870
1-2-2	Universal	Hand	1	60	1	332	6	2696
1-2-3	Universal	Hand	1	61	1	302	3	1733
1-2-5	Universal	Hand	1	61	1	122	3	1685
1-2-6	Universal	Hand	1	65	1	113	3	1108
1-2-8	Universal	Hand	1	73	1	117	3	1240
1-2-4	Chicago AA	Hand	6†	100	..	...	18	1700
				1911				
1-2-4	Universal	Hand	11	240	..	...	33	3100
1-2-4	Lehigh	Hand	6	240	..	...	18	2937
				1912				
1-2-4	Universal	Hand	12	63	..	...	36	2200
1-2-4	Universal	Machine	31	63	..	...	93	2800
1-2-4	Universal	Machine	4	240	..	...	12	3774

*** Includes one batch (No. 4) made of Chicago AA cement.**
† From the concrete used in the 1909 beams.

The compressive strength of 6-in. cubes from the 1912 1-2-4 concrete tested at average age of 63 days was as follows: 36 cubes of hand-mixed concrete, 2200 lb. per sq. in.; 93 cubes of machine-mixed concrete, 2800 lb. per sq. in. The machine-mixed cubes gave about 30% higher strength than the hand-mixed. However, it will be seen later that all of the tests do not bear out this conclusion; in some of the beam tests the hand-mixed concrete gave the higher values for bond and vertical shearing stress.

In making some of the larger batches of concrete for the 1909 pull-out tests a period of from three to four hours elapsed between the making of the first and last specimens. From five batches of this kind a set of three 6-in. cubes was made as soon as the mixing was completed and a second set after about 50 pull-out specimens had been finished. The portion of the batch remaining on the mixing floor was turned two or three times during the interval between making the two sets of cubes. The average compressive strength of five sets of cubes made as soon as the mixing was complete, was 1756 lb. per sq. in. The average for cubes made 3½ hours after mixing, was 1733 lb. per sq. in., a difference of about 1%. It will be remembered that the Vicat needle test showed this cement to reach final set at 3¾ hr.

A. Pull-out Tests.

16. *Classification of Pull-out Tests.*—A total of 1500 pull-out tests are reported in this bulletin. The 1909 series included about 1000 pull-out specimens. Forty-two pull-out specimens were made as companion pieces to the 1911 series of reinforced concrete beams, and 180 with the 1912 series of beams. The remainder of the pull-out tests are grouped under "Miscellaneous Tests," Art. 54 to 64.

The pull-out tests will be discussed under eight different headings as shown in Table 6, which indicates the number of tests included under each sub-division and the tables and figures in which details of the tests may be found. An inspection of the table will show that these divisions are not exclusive, as such elements as effect of age, proportions of concrete, condition of storage, etc., are found to be important variables in more than one of the groups. A few tests are included under two sub-divisions, but this is indicated in the tables of test data. However, each sub-division may be considered as a more or less complete series of tests, and they were so considered in designing and making the specimens. In making comparisons between different groups, the conditions of storage and the quality of the concrete as shown by the cube tests, should be taken into consideration.

TABLE 6.

CLASSIFICATION OF PULL-OUT TESTS.

Item	Number of Tests	Test Data in	
		Tables No.	Figures No.
a. Effect of Variations in the Dimensions of Pull-out Specimens	163	7, 8, 9, 10	5 to 16
b. Effect of Shape of Section and Condition of Surface of Bar	90	11	17, 18
c. Effect of Condition of Storage	189	1	19, 20
d. Bond Tests with Deformed Bars	116	13, 14, 15	21 to 26
e. Effect of Age and Mix	265	16, 17, 18	27 to 35
f. Effect of Anchoring End of Bar	97	19	36, 37
g. Miscellaneous Tests	357	20, 21, 22, 24	38 to 45
Companion Tests to Reinforced Concrete Beams	222	28, 29, 30, 32, 33 and 34	49, 55

17. *Stresses and Deformations in a Pull-out Specimen.*—As load is applied to the bar in a pull-out specimen of the form used in these tests, the tensile stress in the bar is gradually taken off along the embedded length by bond between the bar and the surrounding concrete. Thus the total tension in the bar, the total compression over the lower face of the concrete block and the total bond stress between the concrete and steel are equal. The principal stresses existing in a pull-out specimen of the form generally used are indicated in Fig. 4. If we consider the bond stress to be uniformly distributed along the length of the bar, the bond unit stress is:

$$u = \frac{P}{m\,h}$$

where P is the total load on the bar, m is the perimeter of the bar, and h is the length of embedment. It is evident that owing to the elongation in the steel due to tensile stress and the shortening in the concrete block due to compressive stress, acting in opposite directions, the greatest bond stress during the early stages of the test and consequently the first slip between concrete and steel must occur at the point where the bar enters the block, and that slip will always be a little greater here than at points of greater embedment. Experimental verification of this statement will be found in the tests. A numerical example will assist in fixing ideas. Consider a 1-in. round bar embedded 8 in. in an 8-in. cylinder. Tests show that a specimen of these dimensions, of 1-2-4 concrete about 60 days old, will withstand a bond stress of about 260 lb. per sq. in. before slip begins. At this stress the total compression in the concrete and tension in the bar are each 6500 lb. The stresses in the concrete and in the steel are 132 and 8300 lb. per sq. in., respectively. If we assume that the deformations in the concrete and the steel are proportional to the stress and that the bond stress is uniformly distributed along the length of the bar we shall have 0.0002 in. and 0.0011 in. for the total deformation in the concrete and steel, using 2 500 000 and 30 000 000 lb. per sq. in., respectively, as the moduli of elasticity

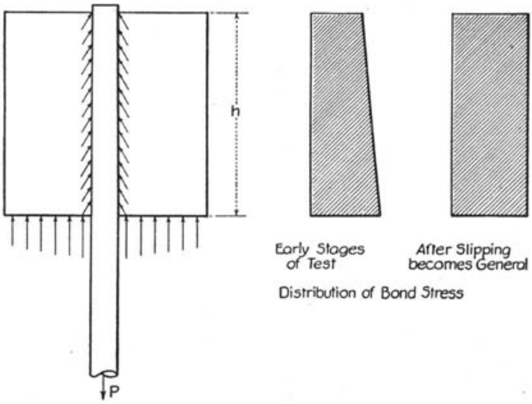


FIG. 4. DIAGRAM SHOWING PRINCIPAL STRESSES IN A PULL-OUT SPECIMEN.

of the materials. This gives a total slip at the lower end of the block of 0.0013 in. when slip at the free end first becomes perceptible. These considerations show that for a 1-in. bar the relative movement at the bottom due to steel deformation is over five times as great as that due to concrete deformation, and indicate that as far as the bond resistance is concerned the compressive stress developed in the concrete block is of minor importance as compared with the steel stress. For smaller bars the influence of the concrete stress is negligible.

As an extreme case consider a 1¼-in. plain bar embedded 24 in. as in the tests in Table 9. Slipping at the free end of the bar began at an average bond stress of 278 lb. per sq. in. The average compressive stress over the lower face of the concrete block at this stage of the test was 540 lb. per sq. in. and the tensile stress in the bar, 21 300 lb. per sq. in. If the bond stress be considered uniformly distributed along the length of the bar, this gives a slip of 0.0112 in. at the bottom when slip at the top of the block begins. It will be found that for specimens of the form generally used in these tests, the bond resistance of plain bars increased as slip progressed and reached a maximum when the bar had slipped about 0.01 in. The tests on 1¼-in. plain bars in Table 9 and Fig. 11 bear out the conclusion that was reached from these computations, that with 24-in. embedment, the maximum bond resistance of the bar as a whole does not differ much from that corresponding to first slip at the free end.

In addition to the longitudinal stresses set up in the concrete and steel, stresses are developed normal to the surface of the bar. During the later stages of the test these stresses become considerable and may be sufficient to split the concrete surrounding the bar. This is especially evident with deformed bars, though the splitting action was found with plain bars.

18. *Phenomena of Pull-out Tests.*—Fig. 6 summarizes load-slip curves for plain round bars for a variety of conditions of age, mix, size of bar, length of embedment and storage. Each curve is a composite of from 5 to 10 tests. For ease of making comparisons all bond stresses have been plotted as a percentage of the maximum bond resistance. Only the portions of the curves preceding the maximum are plotted here; all of these tests are discussed in detail in the following pages. These curves are quite similar, considering the wide variations of conditions present. Attention should be called to the fact that in this figure the values of slip of bar were measured at the free end. Generally, slip at the free end began at a load between 60% and 80% of the maximum. In nearly all cases the maximum load occurred at an end slip of about 0.01 in. It seems that a movement of 0.01 in. between the concrete and steel was sufficient to destroy the irregularities which were most effective in increasing bond resistance after the adhesion was broken.

The curves in Fig. 5 represent the successive condition at each point along the length of the bar. The basis of these curves is given in Arts. 19, 22 and 23. The solid curve may be considered as typical of the load-slip relation found in pull-out tests with plain bars. This curve represents what may be considered as the bond-stress-slip history of each unit of the embedded length of a plain bar. It exhibits the following characteristics:

(1) There is no measurable slip of bar until a bond stress of about 260 lb. per sq. in. has been developed.

(2) Slipping begins at about 60% of the maximum bond resistance.

(3) When the bar has slipped 0.001 in. at any point the bond stress there is about 75% of the maximum bond resistance.

(4) When the slip at any point reaches 0.005 in. the bond stress there is 95% of the maximum.

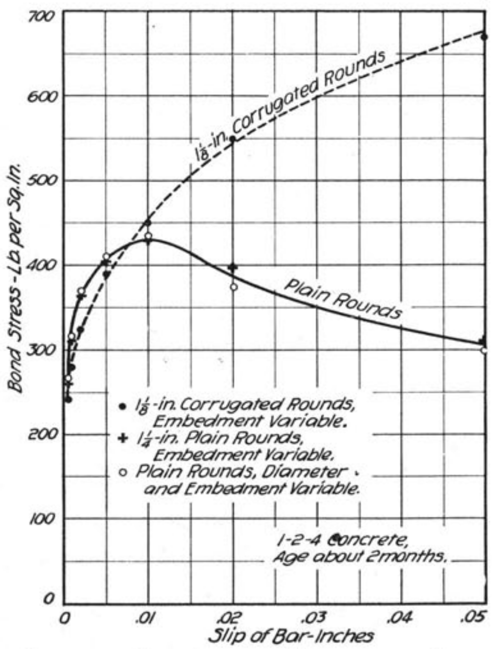


FIG. 5. LOAD-SLIP CURVES AFTER ELIMINATING SIZE OF BAR AND LENGTH OF EMBEDMENT.

(5) The maximum bond resistance occurs at a slip of about 0.01 in., and the bond resistance decreases with further movement of the bar.

(6) When the bar has slipped twice the amount which was measured at the maximum bond resistance the bond stress has decreased only 10%.

(7) When the bar has moved 0.05 in., five times the slip at the maximum bond resistance, the bond stress is still about 70% of the maximum.

The curve shows that the term "running friction" loses its significance in view of the data of these tests, since, properly speaking, we are dealing with "running friction" throughout the test after movement begins.

It should be borne in mind that these deductions apply only to test specimens of the form used, under a progressively applied load that does not exceed the yield point strength of the bar. It will be seen later that the continuation of a constant load after slipping has begun, and other variations materially modify the load-slip relation. The broken line in Fig. 5, from a series of tests on corrugated round bars, indicates the corresponding load-slip relations for this type of bar.

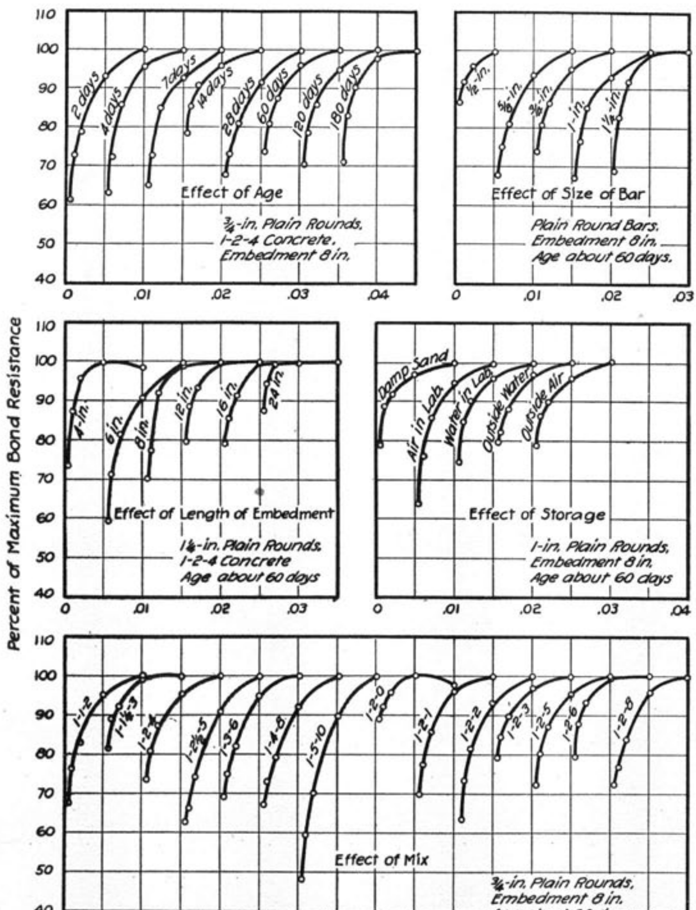


FIG. 6. LOAD-SLIP CURVES FROM PULL-OUT TESTS WITH PLAIN ROUND BARS.

a—Effect of Variations in the Dimensions of Pull-out Specimens.

19. *Effect of Size of Plain Bars; Embedment Variable.*—In this group of tests the diameter of the concrete cylinders for all the specimens was 8 in., but the size of bar and length of embedment varied as shown in Table 7, between the limits ¼-in. plain round bar embedded 3 in. and 1¼-in. round bar embedded 16 in. It will be seen that these dimensions are such as to give a nearly constant ratio (about 50) be-

TABLE 7.

EFFECT OF SIZE OF BAR; EMBEDMENT VARIABLE.

Diameter of concrete cylinders 8 in. in all cases.

1-2-4 hand-mixed concrete from Batches 11, 22, 25, 31, and 36. (See Table 4.)

The average compressive strength of 18 6-in. cubes from this concrete, tested at age of about 60 days, was 1975 lb. per sq. in.

Stresses are given in pounds per square inch.

Size of Bar	Length of Embedment		Number of Tests	Age at Test	Bond Stress at End of Slip of		Maximum Bond Resistance
	inches	diameters		days	.0005 in.	.001 in.	
Plain Round Bars.							
¼ in.	3	12.0	4	71	376	389	476
⅜ in.	4¾	12.6	4	73	335	371	423
½ in.	6	12.0	5	71	263	316	408
⅝ in.°	8	12.8	5°	72	266	295	405
¾ in.	9½	12.6	5	70	287	311	386
1 in.	12¾	12.8	6	70	305	327	392
1¼ in.*	16	12.8	9*	75	275	298	359
Average......	....	....	....	72	301	330	407
Corrugated Bars.							
¼ in. sq.	3½	17.5	5	71	282	335	739†
⅜ in. sq.	4½	15.0	4	71	324	356	...
½ in. sq.	8	16.0	5	71	341	371	702†
¾ in. sq.	12	16.0	5	71	339	367	730†
1⅛ in. rd.*	24	19.2	9*	77	268	301	688†
Average......	....	....	....	72	311	346	715†

° The same tests are included in Table 8.
* Includes 4 tests made with group in Table 9.
† Blocks were reinforced against bursting by means of ¼-in. spirals. The maximum bond stress given in the tables for corrugated bars is the average stress developed at an end slip of 0.1 in.

tween the embedded area and the cross sectional area of the bar and corresponds to an embedment of about 12 diameters for each of the bars. It was felt that this was the proper basis for a series of tests to show the relation between the bond resistance and the size of bar. The load-slip curves are plotted in the upper portion of Fig. 7. In Fig. 8 the loads have been plotted for slips at the free end of the bar of 0.0005,

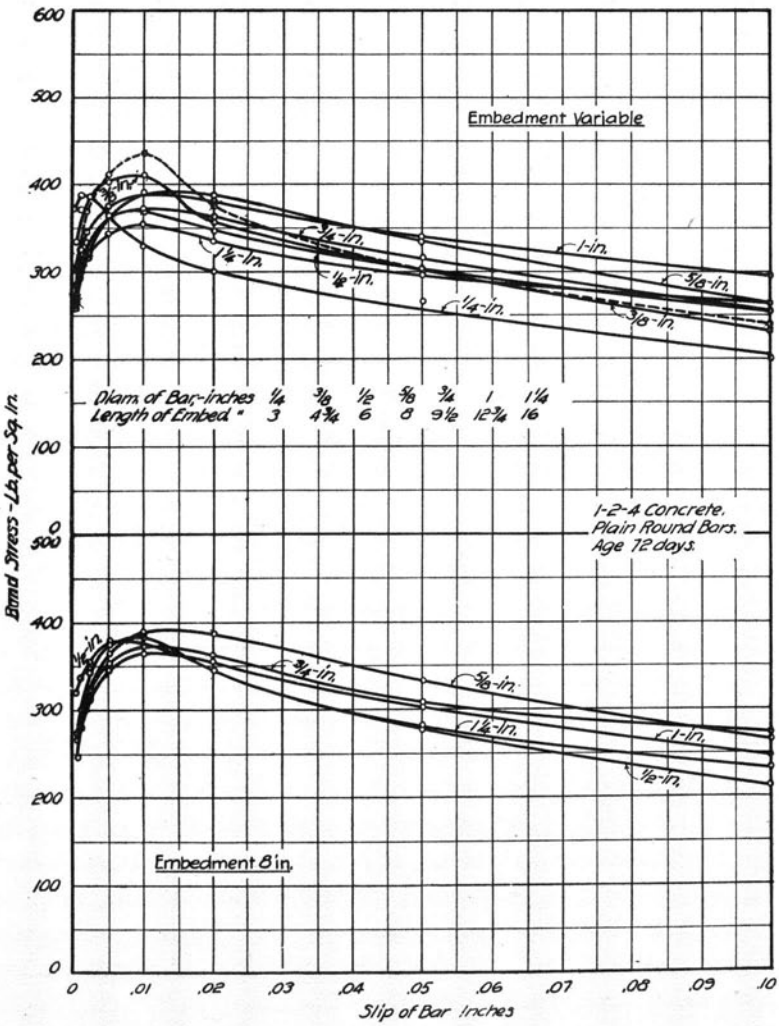


FIG. 7. LOAD-SLIP CURVES FOR PLAIN ROUND BARS OF DIFFERENT SIZE.

0.001, 0.002, 0.005 in. and for the maximum bond resistance, corresponding to a slip of about 0.01 in.; the corresponding points are connected by straight lines. A slip of 0.0005 in. may be considered as the beginning of slip.

In general the smaller bars gave a bond resistance slightly higher than the bars of larger size, but the relation is not well defined at all stages of the tests. The maximum bond resistance decreased as the diameter of the bar increased. The ⅜-in. bars gave values at the maximum load about 15% higher than the 1¼-in. bars. The ¼-in. bars embedded 3 in. were somewhat erratic in their behavior. Some of the

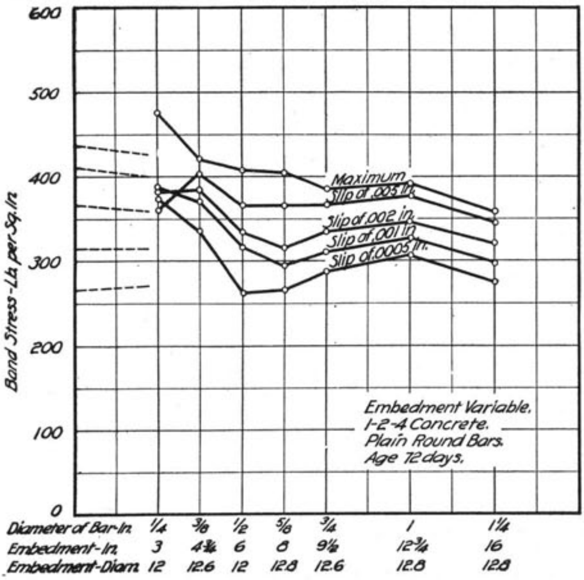


FIG. 8. BOND RESISTANCE OF PLAIN ROUND BARS; EMBEDMENT VARIABLE.

concrete blocks split at the maximum load. The cause for this is somewhat problematical, but it probably was due to slight irregularities in the contact between the concrete block and the bearing plate and to lack of stiffness in the blocks which prevented them from distributing the compressive stress over their entire base.

With a constant ratio between the average bond stress throughout the length of the bar and the tensile stress in the steel, that is, with the bars embedded a constant multiple of the diameter, there are several variables which may affect the bond stresses developed. Among these may be mentioned:

(1) Variation in the compressive stress in the concrete block;

(2) Contraction in the section of the bar due to the tensile stress;

(3) Variations in the section and alignment of bars of different sizes.

(1) The compressive stress in the concrete blocks in these tests varies directly with the section of the bar, if the bond unit stress is the same. The maximum compressive stress at the bottom of the concrete blocks in the tests on the ½-in. bars embedded 6 in. and on the 1¼-in. bars embedded 16 in. are 76 and 622 lb. per sq. in., respectively, using 400 lb. per sq. in. bond stress in both cases. It is evident from these tests and the tests discussed in Art. 21 and 22 that a wide variation in the amount of compressive stress in the concrete block has very little influence on the bond stresses developed in the tests.

(2) The total contraction of the section of the bar due to tensile stress will be proportional to the diameter of the bar for the same unit stress in the steel. For the 1¼-in. bars used in this group of tests the diameter of the bar is shortened as much as 0.0004 in. when it is carrying the highest stress. A portion of this shortening was counteracted by the corresponding expansion in the concrete, but since the distribution of the concrete stresses is not known and the amount of this expansion uncertain, the relation of these deformations cannot be determined. It seems that the contraction in the section of the bar may have a slight influence in reducing the bond resistance of the larger bars for loads near the maximum. This influence would not be important in the group of tests discussed in Art. 22, since the steel stresses were not high.

(3) The bars used presented surfaces which apparently were similar in all respects. It has frequently been observed, however, that small rolled bars are more irregular in section and alignment than larger bars. This fact may partially account for the higher stresses developed by the smaller bars in the later stages of the tests. The lower bond stress developed by the smaller bars after an end slip of 0.01 in. has occurred lends color to this opinion.

These tests indicate that small bars give a somewhat higher bond resistance than larger bars. Earlier discussions of this subject have been based on the maximum bond stresses developed by bars of different sizes embedded equally without regard to the load-slip relations present. A group of tests of this kind is discussed in the following article.

In Fig. 8 dotted lines have been drawn which indicate the general trend of the values of bond resistance in these tests for the various amounts of slip. In constructing these lines least weight has been given to the values for 1/4 and 3/8-in. bars, since the load-slip curves in Fig. 7 show these tests to be abnormal. The points at which these lines intersect the vertical axis may be said to represent the bond stresses for a bar of infinitesimal diameter embedded an infinitesimal length; the embedded length is still equal to about 12 diameters. These values and values obtained in a similar way from Fig. 12 have been used to plot the load-slip curve shown by the solid line in Fig. 5. It will be seen that the values given in the figure for the two series of tests are nearly identical. This curve may be said to show the successive variations in bond resistance at each point along the length of the bar during the progress of the test after eliminating the size of bar and length of embedment. This consideration shows slipping to have begun at a somewhat lower load than was indicated by the measurements of slip at the free end of the bar and that the maximum bond resistance from point to point was a little higher than that found for the bar as a whole. This is as might have been expected, since, up to the load at which slip reached a considerable amount and became general, each point along the length of the embedded bar was in a different stage of its load-slip history. After the maximum load the curve for infinitesimal embedment follows the general course of the other curves, which indicates that after the adhesion was entirely broken and slip became general, the frictional resistance was about the same for all sizes of bars of the kind used in these tests. It will be seen in the discussion of Fig. 12 in Art. 22 that a curve of almost exactly the same form is found from a consideration of a group of tests on 1 1/4-in. plain rounds in which the length of embedment varied.

20. *Effect of Size of Corrugated Bars; Embedment Variable.*—The group of tests on corrugated bars given in Table 7 may be considered as forming a series parallel to the group of tests on plain rounds discussed in Art. 19; they were made from the same concrete. The specimens varied from a 1/4-in. corrugated square bar embedded 3 1/2 in. to a 1 1/8-in. corrugated round bar embedded 24 in. As in the group of tests on plain rounds these dimensions were such as to give approximately a constant ratio (about 48) of bond area to the cross-sectional area of the bars, corresponding to an embedment of about 16 short diameters of the bars (21.4 diameters in the case of 1 1/8-in. corrugated round bars). The bond resistances for various amounts of end slip are plotted in Fig. 9. The values for 1/3-in. bar embedded 4 1/2 in. have

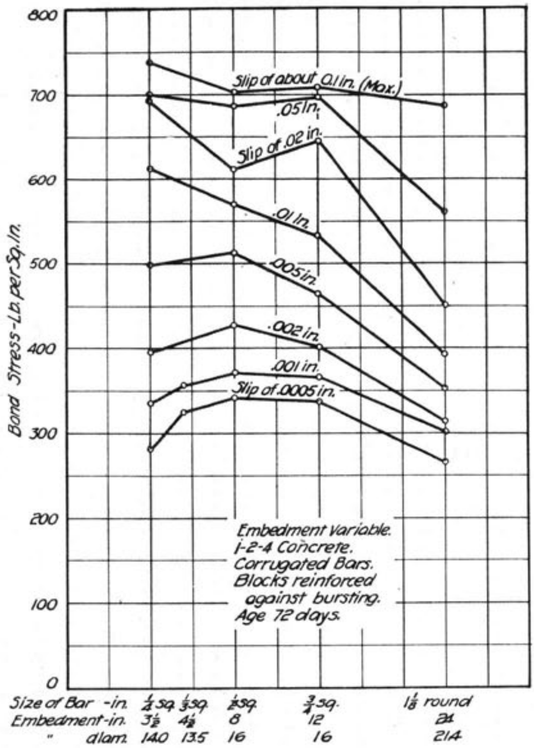


FIG 9. BOND RESISTANCE OF CORRUGATED BARS; EMBEDMENT VARIABLE.

TABLE 8.

EFFECT OF SIZE OF PLAIN ROUND BARS; EMBEDMENT 8 IN.

Made from the same concrete as the tests in Table 7.
Stresses are given in pounds per square inch.

Size of Bar	Length of Embedment		Number of Tests	Age at Test days	Bond Stress at End Slip of		Maximum Bond Resistance
	inches	diameters			.0005 in.	.001 in.	
½ in.	8	16.0	4	72	323	339	381
⅝ in.	8	12.8	5*	72	266	295	405
¾ in.	8	10.7	5†	81	275	303	387
1 in.	8	8.0	5	64	247	281	385
1¼ in.	8	6.4	12‡	74	269	296	397

* The same tests as given in Table 7.
† Note the similarity between these values and those for 9½-in. embedment in Table 7; compare also tests in Table 10.
‡ The same tests as given in Table 9.

been omitted from the table and diagram after a slip of 0.001 in., since the data for some of the tests are not complete; the position of the two points in the figure indicate that the remaining points probably would have occupied their proper places in the diagram.

In general, slipping began at a bond unit-stress only a little greater than for the plain rounds. For end slips of 0.0005 and 0.001 in. the average bond stresses are 301 and 330 lb. per sq. in. for plain rounds and 311 and 336 lb. per sq. in. for the corrugated bars; at this stage of the tests the stresses developed by the plain rounds were about 97% of those given by the corrugated bars. The highest bond stresses reported (end slip of 0.1 in.) are not materially different for the bars of the sizes used in these tests, and average about 715 lb. per sq. in. The somewhat lower values given by the 1⅛-in. corrugated round bars are probably due to the design of this bar as compared with the square bars; the projections on this bar present a smaller area to take the bearing stress which replaces the bond resistance after the failure of the adhesion than the square bars of type B which were used in the other tests in this group.

21. *Effect of Size of Plain Round Bar; Embedment 8 in.*—In this group of tests the diameter of the concrete cylinders was 8 in. and the length of embedment 8 in., while the diameters of the plain round bars used varied from ½ to 1¼ in. The results are summarized in Table 8. The load-slip curves are plotted in the lower portion of Fig. 7. The loads for various amounts of slip of the free ends of the different bars have been plotted in Fig. 10. The broken lines drawn in Fig. 10 show the trend of the values for the different amounts of slip and for the maximum loads. The values for end slip of 0.0005 in. may be taken as the beginning of slip. It is seen that in the earlier stages of the tests, the smaller bars develop the higher bond stresses; the load at beginning of slip of the free end of the bars varies from 323 lb. per sq. in. for the ½-in. rounds to about 253 lb. per sq. in. for the 1 and 1¼-in. bars. The maximum bond resistance is nearly constant and averages 391 lb. per sq. in.

22. *Effect of Length of Embedment; 1¼-in. Plain Rounds.*—In this group of tests the length of embedment varied from 4 to 24 in., corresponding to 3.2 to 19.2 diameters. One and one-fourth-inch bars were used in order to secure a wide range of embedded lengths without overstressing any of the bars. A summary of the tests is given in

Table 9. The load-slip curves have been plotted in Fig. 11. The bond stresses corresponding to various amounts of end slip up to and including the maximum load are shown for the different lengths of embedment in the upper portion of Fig. 12. In the lower part of the figure the maximum resistance and the stresses after the maximum for slips of 0.02 in., 0.05 in. and 0.10 in. are plotted.

The load-slip curve for 4-in. embedment drops off sharply after the maximum load, as a result of the splitting of some of the concrete blocks. Fig. 12 shows that the average bond stress corresponding to

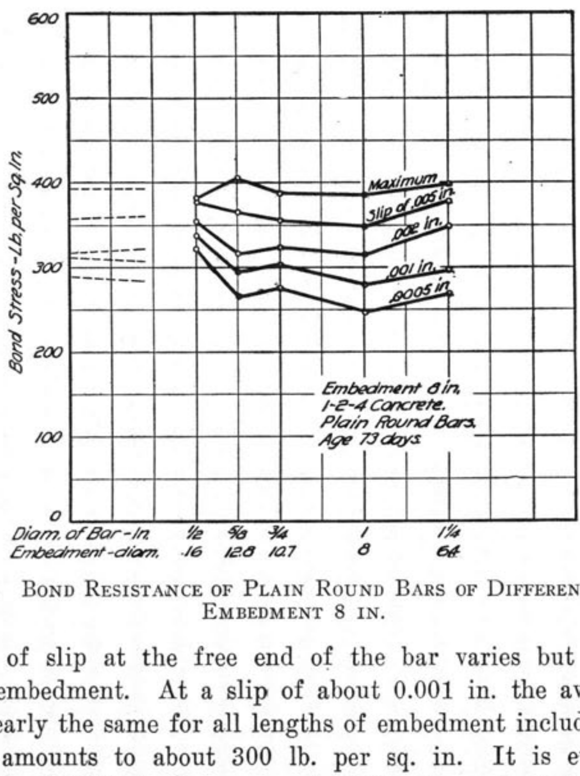


FIG 10. BOND RESISTANCE OF PLAIN ROUND BARS OF DIFFERENT SIZE; EMBEDMENT 8 IN.

beginning of slip at the free end of the bar varies but little with increased embedment. At a slip of about 0.001 in. the average bond stress is nearly the same for all lengths of embedment included in these tests and amounts to about 300 lb. per sq. in. It is evident that when a slip of 0.001 in. has occurred at the free end of the bar, slipping has become general throughout the length of the bar, but it will be seen from a consideration of the conditions present and from the load-slip curves that the amount of slip represents quite different stages of the test in the specimens of different lengths of embedment. For the 4 or 6-in. embedment the difference between the amount of slip at the two ends of the block for any given load is not great, and

TABLE 9.

Effect of Length of Embedment.

1-2-4 concrete from Batches 10, 17, 24, 27 and 30.

Diameter of concrete cylinder 8 in. in all tests.

These specimens were made from the same concrete as the specimens with deformed bars in Table 14.

The average compressive strength of 24 6-in. cubes from same concrete tested at about 60 days was 1760 lb. per sq. in.

Stresses are given in pounds per square inch.

Length of Embedment		Number of Tests	Age at Test days	Bond Stress at End Slip of		Maximum Bond Resistance
inches	diameters			.0005 in.	.001 in.	
1¼-in. Plain Rounds.						
4	3.2	5	74	265	314	375
6	4.8	5	74	243	391	420
8	6.4	12*	74	269	296	397
12	9.6	5	75	284	312	390
16	12.8	9+	75	275	298	359
24	19.2	5	76	278	300	328
1⅛-in. Corrugated Rounds°.						
4	3.6	5	74	228	272	830†
8	7.1	5	86	250	286	775†
16	14.2	5	76	281	306	846†
24	21.4	9+	77	268	301	688†

* Includes five tests made with the group in Table 8 and two tests from Batch 37.

\+ Includes five tests made with the group in Table 7.

° Blocks were reinforced against bursting by means of a ¼-in. spiral.

† Bond stress corresponding to end slip of 0.1 in.

we may expect that the load-slip relations given by these specimens (barring the premature splitting of the 4-in. blocks) are not much different from those for a unit of area at any point along the embedded length of the bar, while for the 24-in. embedment the load-slip relation at the free end of the block must be quite different from that at the other end.

If the straight lines which represent the general trend of the values of bond resistance for the amounts of slip shown in Fig. 12, be extended to the left to intersect the vertical axis of coordinates,

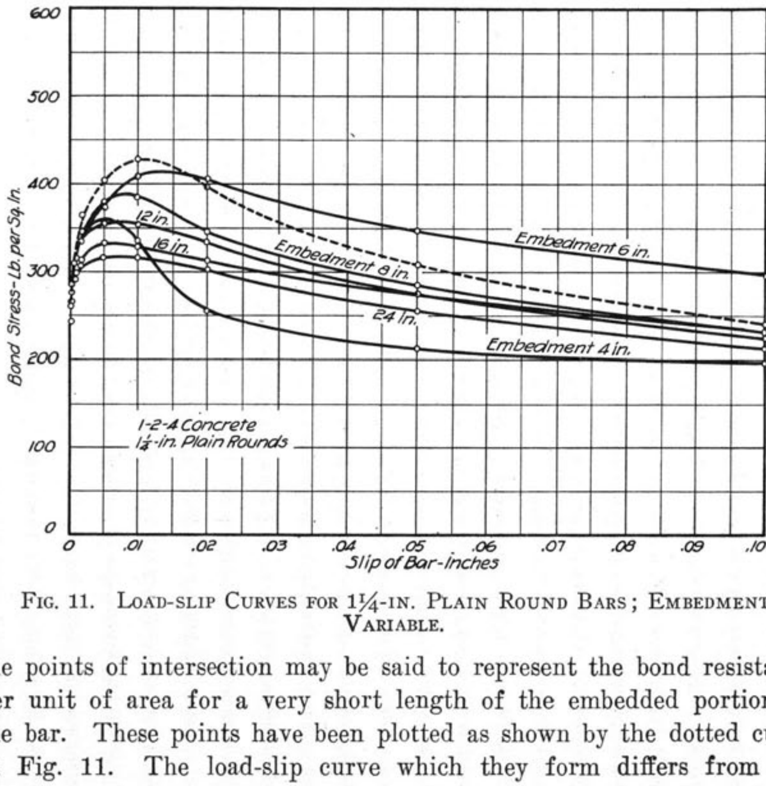


FIG. 11. LOAD-SLIP CURVES FOR 1¼-IN. PLAIN ROUND BARS; EMBEDMENT VARIABLE.

the points of intersection may be said to represent the bond resistance per unit of area for a very short length of the embedded portion of the bar. These points have been plotted as shown by the dotted curve in Fig. 11. The load-slip curve which they form differs from the others in the same group in that slip begins at a somewhat lower proportional load and the bond resistance reaches a higher maximum value than indicated by the other curves, and the curve drops off a little more rapidly after the maximum. This curve may be said to represent the conditions for an infinitesimal embedment of a bar of this kind, and indicates what happens at each point along the embedded length of a bar during the progress of the pull-out tests in

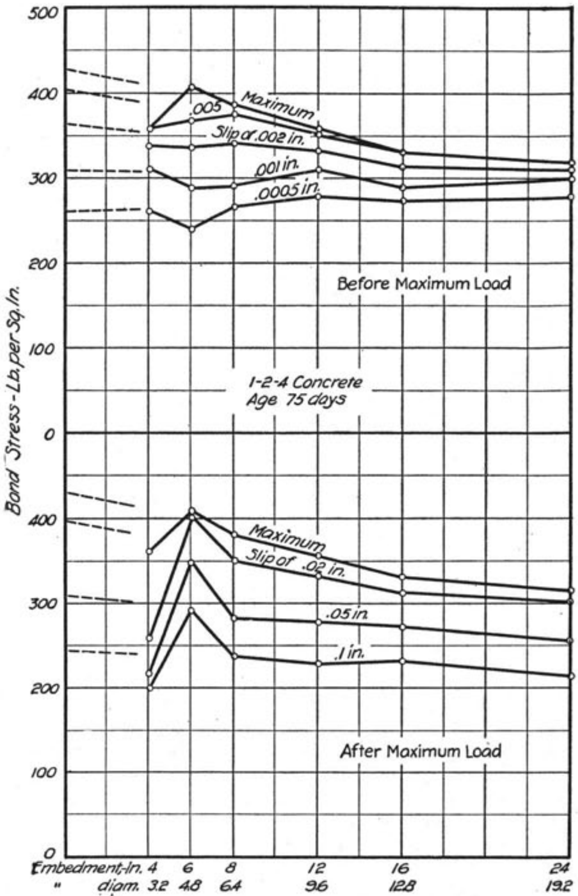


FIG. 12. BOND RESISTANCE OF 1¼-IN. PLAIN ROUND BARS; EMBEDMENT VARIABLE.

the same way as indicated in Art. 19 for another group of tests. The values derived in this way are as dependable as those given for other lengths of embedment, since they are based on the mean stresses from the entire group of tests. Data from these tests were used in plotting the solid curve in Fig. 5. The points in Fig. 5 for the plain round bars were derived from these tests and from the tests discussed in Art. 19. Only one curve has been drawn for the plain bars, although the values from the two series of tests are indicated by distinctive symbols. The similarity of the values obtained in this way is noteworthy, when we consider that these specimens were made from bars of different size and from different batches of concrete. The uniformity of these values gives considerable confidence in the tests and in the conclusions based on them. These values are significant in arriving at a proper conception of bond action for bars of this kind.

The maximum bond stress decreased as the length of embedment increased and varied quite uniformly from 410 lb. per sq. in. for 6 in. embedment to 320 lb. per sq. in. for 24 in. embedment. The lines in the lower division of Fig. 12 converge at a point about 290 lb. per sq. in. bond stress and 30 in. embedment. This indicates that with a longer embedment than 24 diameters the maximum average bond resistance would be less than that which gives first slip with shorter embedments. When a slip of 0.1 in. is reached, approximate equality of bond stress for all lengths of embedment is again found at about 235 lb. per sq. in.

23. *Effect of Length of Embedment; 1⅛-in. Corrugated Rounds; Blocks Reinforced against Bursting.*—The tests with corrugated bars embedded in reinforced blocks summarized in Table 9, may be considered as parallel to the group of tests on plain rounds made from the same concrete and included in the same table. In this group the concrete cylinders were all 8 in. in diameter, but the length of embedment varied from 4 to 24 in. The concrete blocks were reinforced against bursting by means of a ¼-in. wire in the form of a spiral as shown in Fig. 1 (b). The load-slip curves are given for the four lengths of embedment in Fig. 13. Each curve is the composite of all the tests in a set. According to the practice in all tests on deformed bars described in this bulletin, the highest bond stress which has been reported was that developed at an end slip of 0.1 in., although in most of the tests the load continued to rise beyond that point. In Fig. 14 the bond stress corresponding to various amounts of end

slip of the bar have been plotted against the length of embedment. The general direction of each of the zig-zag lines is indicated by the short dotted lines at the left margin of the figure. The points of intersection of these lines with the vertical axis of co-ordinates may be taken to represent the action of a similar bar of infinitesimal embedment, based on the general trend of the values from these tests. The

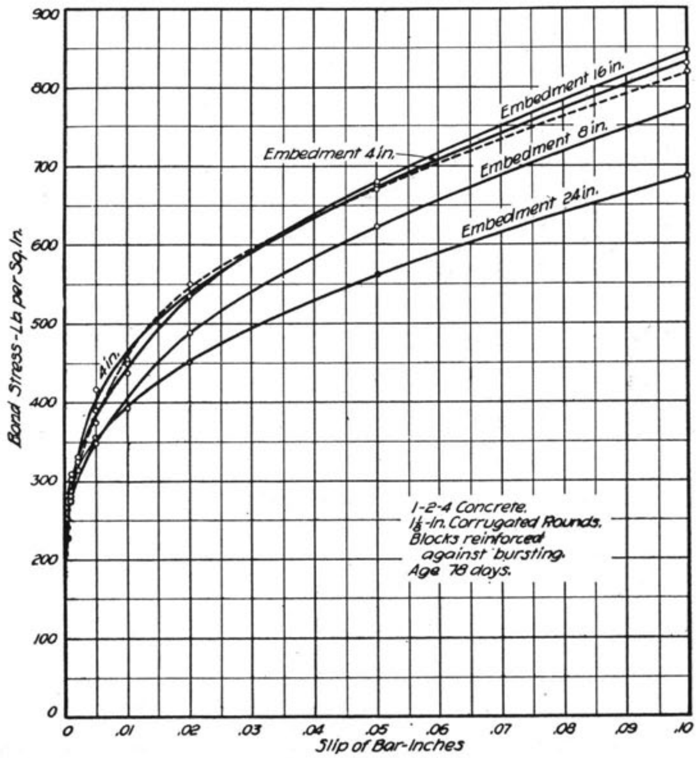


FIG. 13. LOAD-SLIP CURVES FOR 1⅛-IN. CORRUGATED ROUND BARS; EMBEDMENT VARIABLE.

load-slip curve corresponding to these points is shown by the dotted line in Fig. 13. As may be expected, it follows closely the curve for the 4-in. embedded length.

If the lines in Fig. 14 are projected to the right it will be found that they intersect at approximately the same point. The interpretation of this feature of the tests is probably the same as that suggested in the preceding article for plain round bars. For an embedment of more than 56 in. (50 diameters) the excessive deformation developed in the concrete and steel would so modify the distribution of bond stresses that an average stress greater than, say, 320 lb. per sq. in. could not be developed in a pull-out test with a bar of this kind.

In these tests slip began at a lower unit stress and the maximum stress was higher in the specimens of short embedment than in those

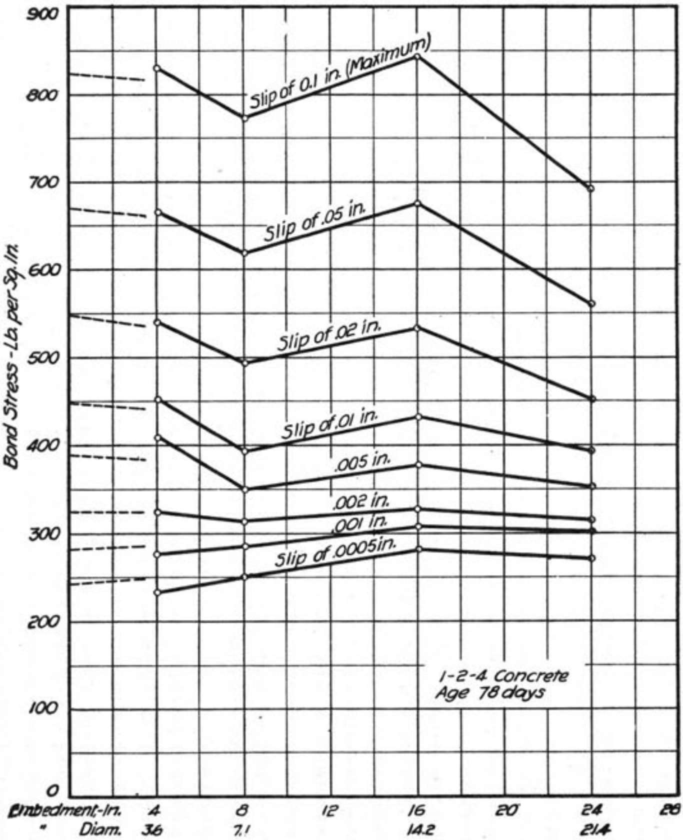


FIG. 14. BOND RESISTANCE OF 1⅛-IN. CORRUGATED ROUND BARS; EMBEDMENT VARIABLE.

of longer embedment. The bond stress at a slip of about 0.002 in. was about the same (320 lb. per sq. in.) for all lengths of embedment included in the tests.

There is a striking similarity between the bond stresses found for the beginning of slip of the 1⅛-in. corrugated round bars and those for the 1¼-in. plain rounds in the preceding article. Up to a slip of about 0.002 in. the plain rounds give slightly higher values at each stage of the tests. It is notable also that the line of equal bond stresses for all lengths of embedment for each of these groups came at a bond stress of about 300 lb. per sq. in. and at approximately the same amount of slip.

The load-slip curve for the $1\frac{1}{8}$-in. corrugated rounds corresponding to an infinitesimal embedment has been plotted in Fig. 5. The interpretation of this curve is much the same as given above for the curve obtained in a similar manner for plain bars and included in the same figure. A comparison of the values for an infinitesimal embedment for this group of tests on $1\frac{1}{8}$-in. corrugated rounds, with the similar curve from the two groups of plain bars discussed in Art. 19 and 22, is of interest. The plain rounds gave higher bond resistance than the corrugated bars for all amounts of end slip up to that corresponding to nearly the maximum resistance of the plain bars; after this point the corrugated bar steadily gained in bond resistance while the bond resistance of the plain bar decreased in the typical manner, after passing a slip of 0.01 in.

Pull-out tests with corrugated bars embedded in concrete blocks without spiral reinforcement are discussed in Art. 64.

24. *Effect of Variation in Diameter of the Concrete Block.*—Table 10 summarizes a group of pull-out tests using $\frac{3}{4}$-in. plain round bars in which the diameters of the concrete cylinders varied from 3 to 12 in. The embedment was 8 in. for all tests except the specimens with 8-in. cylinders which were embedded $9\frac{1}{2}$ in. The load-slip curves for these tests are plotted in Fig. 15. In Fig. 16 the values of bond unit-stress for various amounts of slip and for maximum loads have been plotted. The values for the 3-in. cylinders do not show the usual increase of bond resistance after beginning of end slip. This is probably due to the high compressive stress developed in the concrete; at the maximum load this stress was about 930 lb. per. sq. in. In the 3-in. cylinders slip began at approximately 78% of the maximum load. If we disregard the 3-in. cylinder tests, the bond stresses showed a decided falling-off for all amounts of slip as the diameter of the cylinder increased. The maximum loads varied quite uniformly from 420 lb. per sq. in. for the 4 and 6-in. cylinders to 358 lb. per sq. in. for the 12-in. cylinders. The values for the 12-in. cylinders were about 84% of the average values for the corresponding amount of slip in the 4 and 6-in. cylinders. The difference may be due to variation in relative shrinkage in longitudinal and radial directions.

TABLE 10.

EFFECT OF VARIATION IN DIAMETER OF CONCRETE BLOCK.

All bars ¾-in. plain rounds.
Made from same batches as tests in Table 7.
Stresses are given in pounds per square inch.

Diameter of Concrete Cylinder inches	Length of Embedment inches	Number of Tests	Age at Test days	Bond Stress at End Slip of		Maximum Bond Resistance
				.0005 in.	.001 in.	
3	8	5	71	253	288	326
4	8	5	71	283	319	413
6	8*	5	71	297	333	426*
8	9½°	5	70	287	311	386°
12	8	5	72	245	272	358

* Compare the specimens with ¾-in. bars in Table 8.
° The same tests are given in Table 7.

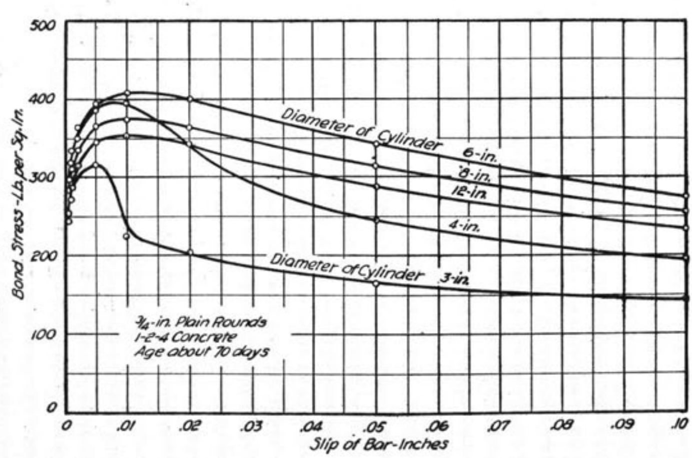


FIG. 15. LOAD-SLIP CURVES FOR ¾-IN. PLAIN ROUND BARS IN CYLINDERS OF DIFFERENT DIAMETERS.

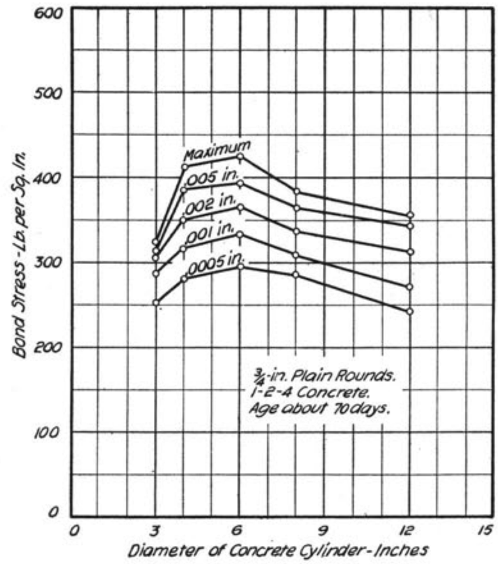


FIG. 16. BOND RESISTANCE OF ¾-IN. PLAIN ROUND BARS IN CYLINDERS OF DIFFERENT DIAMETERS.

b. Effect of Shape of Section and Condition of Surface of Bar.

25. *Bond Resistance with Rusted Bars.*—Fig. 17 gives the load-slip curves for the specimens in Table 11 which have ordinary mill surfaces and rusted surfaces. For the bars having ordinary mill surfaces, end slip began at 267 lb. per sq. in.; the maximum bond resistance was 380 lb. per sq. in. and corresponded to an end slip of 0.01 in. The rusted bars had a heavy coat of firm rust caused by allowing them to remain below the surface in a pile of damp sand for five weeks previous to making the specimens. The tests on rusted bars gave a bond resistance higher than that developed with bars having ordinary mill surfaces. End slip began at 302 lb. per sq. in.; 13% higher than for round bars with ordinary mill surfaces. The maximum bond resistance of the rusted bars was 440 lb. per sq. in.; 16% higher than for ordinary rounds. The load-slip curve shows the maximum bond resistance to come at a somewhat greater slip than in the round bars of ordinary surface; this result is a natural consequence of the rougher surface, which is responsible also for the higher bond resistance developed by the rusted bars.

TABLE 11.

EFFECT OF SHAPE OF SECTION AND CONDITION OF SURFACE OF BAR.

Embedment 8 in.

1-2-4 hand-mixed concrete from Batches 10, 11, 17, 22, 24, 25, 27, 30, 31 and 36.

The average compressive strength of 42 6-in. cubes made from 10 different batches of concrete, tested at about 60 days, was 1850 lb. per sq. in.

All stresses are given in pounds per square inch.

Size and Kind of Bar	Number of Tests	Age at Test days	Bond Stress at End Slip of		Maximum Bond Resistance
			.0005 in.	.001 in.	
Plain Round Bars.					
1-in., ordinary mill surface	5	69	267	302	380
1-in., rusted	5	69	302	331	440
Flat Bars.					
1x½-in.	6	69	359	395	459
2x¼-in.	4	81	239	263	293
T-Bars.					
1x1x⅛-in. (area 0.27 sq. in.)	5	64	282	295	310
1¼x1¼x$\frac{3}{16}$-in. (area 0.48 sq. in.)	5	71	227	282	305
2x2x¼-in. (area 1.07 sq. in.)	5	64	202	221	242
Polished Round Bars.					
1-in., polished	5	69	149	...	152
¾-in. tool steel, polished	5	69	137	146	160
¾-in. tool steel, ordinary surface	6	71	170	192	255
Bars of Wedging Taper*. Polished 1-in. Rounds.					
Tapered 0.025 in. per ft	4	66	171	...	250†
Tapered 0.07 in. per ft	5	69	162	...	482†
Tapered 0.10 in. per ft	5	69	173	...	547†
Tapered 0.20 in. per ft	5	69	163	...	633†
Average	....	68	167		
Bars of Non-Wedging Taper. Polished 1-in. Rounds.					
Tapered 0.025 in. per ft	5	69	164	...	170
Tapered 0.07 in. per ft	5	69	201	...	222
Tapered 0.10 in. per ft	5	69	204	...	210
Tapered 0.20 in. per ft	5	69	150	...	155
Average	....	69	180	....	189

* The concrete blocks were reinforced against splitting by means of a ¼-in. wire in the form of a spiral. See Fig. 18 for sketch of specimen.

† Corresponding to an end slip of 0.1 in.

26. *Bond Resistance with Flat Bars.*—The flat bars presented about the same character of surface as the plain rounds. Through an error in making the test pieces, 6 specimens were made with 1 by ½-in. bars and 4 with 2 by ¼-in. bars. Direct comparison of the results of the tests is not as convincing as it might have been with an equal number of specimens of each size. The load-slip curves are plotted in Fig. 17. The 1 by ½-in. bars show a higher bond resistance and the 2 by ¼-in. bars a lower bond resistance than the corresponding plain rounds.

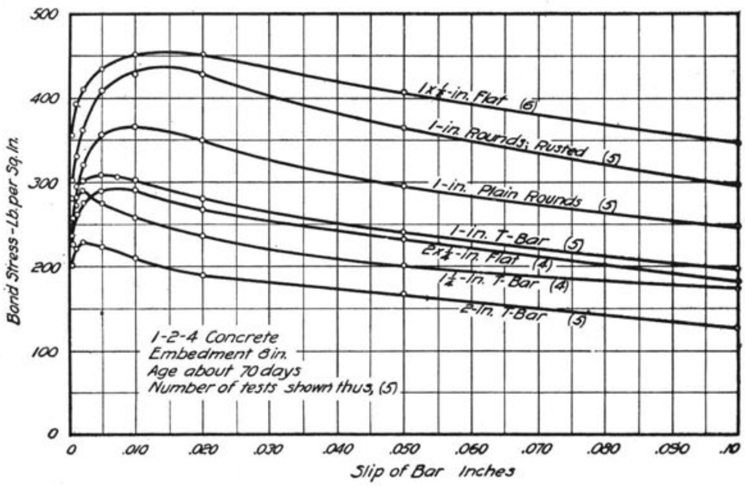


FIG. 17. LOAD-SLIP CURVES FOR PLAIN ROUND, FLAT AND T-BARS.

27. *Bond Resistance with T-bars.*—Pull-out tests were made on three sizes of T-bars, 1, 1¼ and 2-in., as shown in Table 11. The bond-slip curves in Fig. 17 show that the bond resistance for the T-bars reaches a maximum at a smaller amount of slip than for the rounds or flats; this is especially true of the larger sizes. The curves for the 1¼-in. and 2-in. T-bars drop off more sharply than usual immediately after the maximum. The smaller T-bars develop higher bond stresses than the larger ones, but all the values fall below those for the plain rounds. On the other hand the bond resistance per lineal inch of bar is twice as high for the 2-in. T-bars as for the 1-in. plain rounds, and the bond resistance per lineal inch for the 1-in. T-bar is about the same as for the 1-in. round.

28. *Bond Resistance with Polished Round Bars.*—A comparison of the bond resistance with polished bars and that with plain bars of the ordinary mill rolling may be expected to show how much of the bond is due to adhesive resistance and how much is due to what has been termed sliding resistance, resulting from irregularities of the surface of ordinary mill steel, and to inequalities in the section or alignment of the bars usually furnished for reinforced concrete construction. In other words, to what degree does the plain bar partake of the nature of a deformed bar? Two sets of tests were made on polished round bars; see Table 11. The 1-in. polished bars were round cold-rolled steel; they were polished by turning rapidly in a lathe and applying fine emery cloth. The ¾-in. tool steel was used as it came from the rolls; these bars had the smooth surface and uniform diameter which are usually found in bars of this kind.

It was characteristic of the tests of specimens with polished bars that as soon as an end slip amounting to between 0.0005 and 0.001 in. was developed, the adhesion was suddenly destroyed and the bar pulled out so rapidly that it was generally impossible to weigh the decreasing load on the testing machine. However, readings were obtained in one test, and the load-slip relation has been plotted in the lowest curve of Fig. 18. This curve differs from those of plain round bars in that the maximum load comes at the very beginning of slip and the curve drops off quite rapidly as soon as slip becomes appreciable.

The mean values of bond resistance from five tests each on ¾ and 1-in. polished bars are 143 lb. per sq. in. at slip of 0.0005 in. and 156 lb. per sq. in. at the maximum. The corresponding values for the 1-in. bars of ordinary surface are 267 and 380 lb. per sq. in. If special weight is given to the bond stresses developed for a small amount of slip, it may be said that the adhesive resistance of clean steel to concrete of this quality is about 150 lb. per sq. in., which amounts to about 55% of the bond resistance of bars of ordinary mill surface at a small amount of slip.

The results of the pull-out tests with tool steel bars having the original surface take a mean position between the values for the polished bars and ordinary plain round bars. Tests reported in Bulletin No. 1 (also in Table 25, Bulletin No. 8), University of Illinois Engineering Experiment Station, gave 136 and 147 lb. per sq. in. as the maximum bond resistance of 1-in. cold rolled bars, and ¾-in. round tool steel bars, respectively, embedded 6 in. in 1-3-6 concrete, and tested at 60 days. The pull-out tests on specimens with cold rolled round bars in which the concrete set under pressures of 100 lb. per sq. in. gave values about 10% higher than those in concrete setting without pressure (see Table 22.) The tests on the effect of loads reapplied after failure of bond on specimens in which smooth bars were used are discussed in Art. 60. Double pull-out specimens with cold rolled rounds are discussed in Art. 61.

29. *Tests with Tapered Bars.*—The tests on tapered bars were designed to throw light on the nature of bond resistance. Tapered bars of two distinct types were used. These types will be referred to as bars with wedging taper and bars with non-wedging taper. The form of the wedging-taper bar is shown in Fig. 18. Four different degrees of taper were used for each type. The taper varied from 0.025 to 0.2 in. per foot for each of the two forms. These bars were polished after machining so as to reduce them to a surface condition as nearly uniform as possible. The specimens with bars with wedging taper were reinforced against bursting by means of 6 or 7 turns of ¼-in. wire in the form of a spiral.

The results of the tests are given in Table 11. The bars with non-wedging taper developed an end slip of less than 0.001 in. and an average maximum bond resistance of 189 lb. per sq. in. before the adhesion was destroyed. Almost immediately the bond resistance fell to nothing. In only a few of the tests did the bar slip as much as 0.001 in. before the maximum resistance was reached. There was no apparent difference in the amount of slip developed before failure in the bars of the different degrees of taper, and there was no systematic relation between bond resistance and amount of taper. These bars gave approximately the same maximum bond resistance as the straight polished bars.

The tests on bars with wedging taper gave average loads for all the tests at the beginning of slip nearly the same as the average for the bars with non-wedging taper for the same amount of slip. The phenomena of these tests were quite different from those of other forms of polished bars or bars with mill surface, and exhibited some unusual features. The uniformity of the loads at first end slip is noteworthy. The load-slip curves for the bars with wedging taper are given in Fig. 18. Each curve is a composite of all the tests in a set. For comparison the load-slip curves for a single test on a straight polished bar and for the set of plain rounds with mill surface have been plotted on the same diagram.

It should be noted that the concrete blocks in this group of tests were reinforced against bursting and this allowed very high bond stresses to be developed. Up to the time that slip began, the bond stress developed was much the same as in the tests with the cylindrical polished bars; and it was not materially different from that found in the tests with the bars with non-wedging taper. In all the tests except those with a taper of 0.2 in. per ft., after a slip of about 0.005 in., corresponding to a bond stress of about 205 lb. per sq. in., the load dropped off as the bar was being withdrawn. With continued slip (the amount

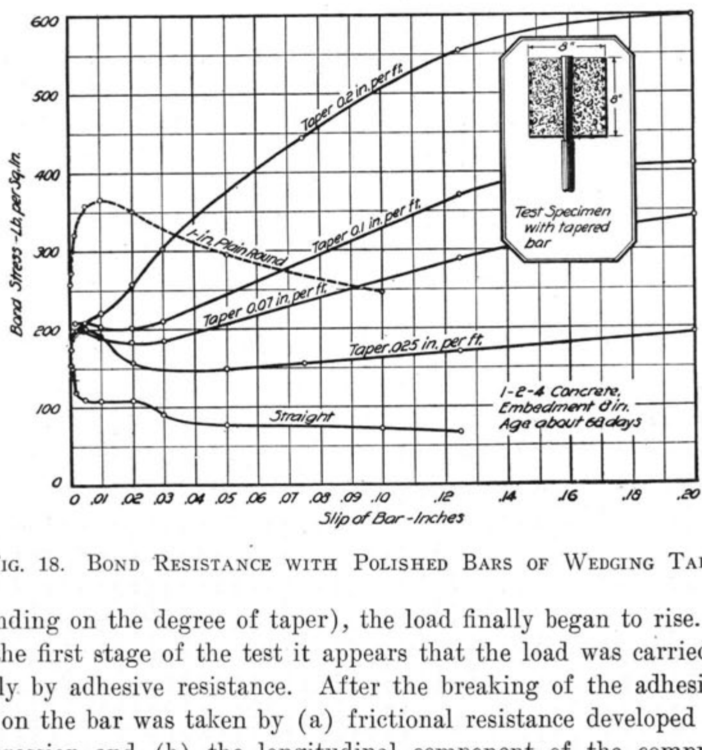


FIG. 18. BOND RESISTANCE WITH POLISHED BARS OF WEDGING TAPER.

depending on the degree of taper), the load finally began to rise. During the first stage of the test it appears that the load was carried principally by adhesive resistance. After the breaking of the adhesion the load on the bar was taken by (a) frictional resistance developed by the compression and (b) the longitudinal component of the compression. The latter was small except with the largest tapers. That the break in the curves is a result of failure in adhesion is shown by the similarity of the stresses up to a slip of about 0.005 in., and by the fact that this bond stress is only a little higher than that found in the tests of polished straight bars and polished bars with non-wedging tapers. These load-slip curves indicate that after adhesion was destroyed the bar slipped an amount which gave only a very small increase in diameter of section—less than 0.0005 in.—before the bond resistance again reached the maximum amount taken before adhesion was destroyed. As slip continued, the amount of increase in diameter at a given section of the concrete block, which corresponds to an additional bond resistance of 100 lb. per sq. in., was about 0.0005 in., being nearly the same for the several tapers. This change of diameter accompanied the compressive stress set up in the concrete. If the coefficient of friction between concrete and steel be taken at 0.25, the calculated normal compressive unit-stress between the concrete and steel will range from two to four times the bond unit-stress; the former figure being for the largest taper. It will be noted that for the larger tapers at the higher loads the load-slip curves change character and round off toward uniform bond resistance. It seems evident that this condition is due to the very high normal compressive stresses in the concrete.

The most notable feature of these tests is the sharp line of demarkation between the effect of adhesion and the effect of wedging action. The similarity of the behavior of the bars with wedging taper and the twisted square bars is discussed in Art. 41.

c. *Effect of Condition of Storage.*

30. *Preliminary.*—It is a not uncommon belief that the permanency of submerged concrete work reinforced with plain bars may be seriously impaired by the ultimate failure of the bond between the concrete and steel. With a view to obtaining information on the effect of a variety of conditions of storage the tests summarized in Table 12 were made. The tests were generally made at age of about 60 days. In two of the groups the age at test varied from 7 days to about 3 years. All specimens, except those placed out-doors, were stored in the Hydraulic Laboratory. Thus the air-stored specimens were in a warm, damp atmosphere. The water-stored specimens were generally tested about 1 to 6 hours after removal from the water. Table 12 also contains the results of the compression tests of 6-in. cubes which were stored under the same conditions as the corresponding pull-out specimens.

31. *Batches 3 and 4.*—From batches 3 and 4 two nearly parallel groups of tests were made using different cements. Five specimens were made for each condition of storage and all tests were made at about 60 days. These specimens were made on January 12 and 13. Twenty-four hours after making, the forms were removed and the speci-

TABLE 12.

Effect of Condition of Storage.

1-2-4 hand-mixed concrete. Embedment 8 in.
Specimens were stored indoors unless otherwise noted.
Stresses are given in pounds per square inch.

Size of Round Bar inches	Age at Test days	Number of Tests	Storage	Bond Stress at End Slip of 0.0005 inches	Bond Stress at End Slip of 0.001 inches	Maximum Bond Resistance	Compressive Strength of 6-in. Cubes, Average of 3 Tests
			Batch 3, Universal Cement.				
¾	62	5	Damp sand	556	620	702	2898
¾	60	5	Air in laboratory	313	375	498	1937
¾	62	5	Water in laboratory	493	562	670	3253
¾	62	5	Water outdoors	413	421	523	2558
¾	63	5	Outdoors in air	354	389	454	2022
			Batch 4*, Chicago AA Cement.				
¾	61	5	Damp sand	387	421	538	1913
¾	50	5	Air in laboratory	246	278	398	1295
¾	62	5	Water in laboratory	359	405	522	1993
¾	61	5	Water outdoors	415	447	539	1677
¾	62	5	Outdoors in air	335	366	489	1642
¾	62	5	Made outdoors in freezing weather	64	67	80	....
			Batch 35, Universal Cement.				
1	7	3	Air	200	224	301	....
1	7	3	Water	239	273	392	....
1	41	3	Air	283	314	491	....
1	41	3	Water	465	514	607	....
1	41	3	Damp sand	429	482	606	....
1	60	3	Air	221	254	416	....
1	60	3	Water	415	492	601	....
1	60	3	Damp sand	475	485	601	3040
1	14 mo.	3	Air	332	389	562	....
1	14 mo.	3	Water	635	731	817	....
1	26 mo.	8	Air	445	513	668	....
1	26 mo.	3	Water	624	772	950	....

* It should be noted that Batch 4 was a much leaner mix than Batch 3; the percentages of cement by weight are 12.7 and 15.4, respectively. The tests in Table 1 show that these two cements were of about equal strength.

TABLE 12—Continued.

Effect of Condition of Storage.

1-2-4 hand-mixed concrete. Embedment 8 in.
Specimens were stored indoors unless otherwise noted.
Stresses are given in pounds per square inch.

Size of Round Bar inches	Age at Test days	Number of Tests	Storage	Bond Stress at End Slip of 0.0005 inches	Bond Stress at End Slip of 0.001 inches	Maximum Bond Resistance	Compressive Strength of 6-in. Cubes Average of 3 Tests
			Batch 41, Universal Cement.				
1	7	2	Air	243	279	381	....
1	7	2	Water	281	343	450	....
1	7	5	Water 4 days; air 3 days	253	285	380	....
1	31	2	Damp sand	456	528	694	2550
1	31	2	Air	309	426	632	2190
1	31	2	Water	383	437	640	2203
1	31	5	Water 14 days; air 17 days	417	465	562	2484
1	60	2	Damp sand	395	440	608	2560
1	60	2	Air	381	439	586	2650
1	60	2	Water	506	600	732	2420
1	60	5	Water 30 days; air 30 days	532	598	691	3160
1	14 mo.	2	Damp sand	821	967	1060	....
1	14 mo.	2	Air	576	668	806	....
1	14 mo.	5	Water 3 mo.; air 11 mo	669	739	848	....
1	26 mo.	2	Air	531	656	815	....
1	26 mo.	2	Water	676	836	984	....
1	37 mo.	4	Water	750	780	936	....
			Batch 39†, Universal Cement.				
¾	61	4	Water 50 days; air 11 days	495	532	671	2360
1¼	61	4	Water 50 days; air 11 days	430	477	634	....
¾	61	4	Water 55 days; air 6 days	476	517	641	2560
1¼	61	4	Water 55 days; air 6 days	431	483	572	....
¾	61	4	Water 58 days; air 3 days	504	554	709	3007
1¼	61	4	Water 58 days; air 3 days	437	498	621	....
¾	61	4	Water 61 days	387	559	658	3020
1¼	61	4	Water 61 days	318	449	471	....
¾	70	4	Water 60 days; air 10 days	586	648	789	3223
1¼	70	4	Water 60 days; air 10 days	392	451	594	....
¾	79	4	Water 60 days; air 19 days	561	673	766	2713
1¼	79	4	Water 60 days; air 19 days	460	536	619	....

† The compressive strength of 6-in. cubes from Batch 39 which were stored in damp sand and tested at abou 60 days was 2190 lb. per sq. in.

mens stored as indicated in the table. The specimens stored out-doors in air were placed near the north wall of the building, where they were exposed to the weather during the greater part of an unusually severe winter. The specimens marked "made outdoors in freezing weather" were made at about noon with the thermometer at 15° F. The concrete was mixed indoors and carried to the forms in buckets. The specimens were left outdoors till the time of test. The concrete probably froze and thawed several times before finally hardening. When the specimens were broken up after testing, evidence of freezing could be seen in innumerable fossil-like crystal forms which were distributed throughout

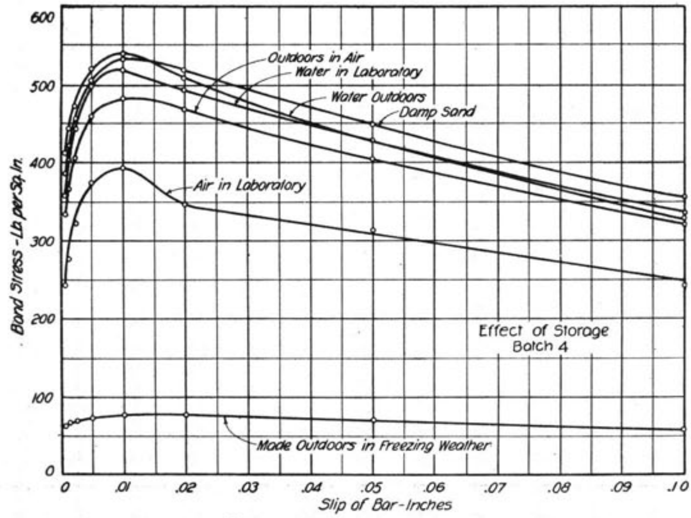


FIG. 19. LOAD-SLIP CURVES FOR DIFFERENT CONDITIONS OF STORAGE.

the concrete. Fig. 19 shows the load-slip curves for the tests from Batch 4; each curve is a composite of the curves for the five tests in a set.

An examination of the values for maximum bond resistance given in the table shows that for both groups the damp sand storage gave the highest resistance, with water storage a close second. For the cube tests, these relations are reversed. There is little difference between the values for water storage indoors and outdoors—an average of 11% in favor of the indoor storage. In the case of air storage the outdoor specimens (average of batches 3 and 4) were 5% stronger than those stored indoors. The average of all water-stored specimens is 23% greater than for the corresponding air-stored specimens. For the cube tests the values are in the same order; the corresponding percentages are 21, 14 and 42, respectively. The similarity of the results for indoor and outdoor storage is surprising when the difference in temperatures is considered. The mean outdoor temperature during the season of storage was 31° F., while the temperature indoors probably seldom fell below 70° F. It seems probable that the loss of water due to evaporation from the specimens indoors in air had more effect in reducing the concrete strength than the low temperature outdoors. The excess of 11% for the water-stored specimens indoors over those stored in water outdoors may be considered to represent the difference in strength due to the higher indoor temperature.

The specimens made outdoors in freezing weather were almost devoid of bond strength. The cubes for this set were accidentally destroyed before the time of test.

The curves in Fig. 19 show considerable similarity in the bond-slip relations of the specimens stored differently. This similarity is maintained until the tests were discontinued at a slip of 0.1 in.

32. *Batch 35.*—In this group a comparison of sand, water and air storage was made for ages varying from 7 days to 26 months. The maximum bond resistances for the different ages for the air-stored and water-stored specimens are plotted in Fig. 20. The values for damp sand and water storage are nearly identical for both ages at which tests were made—41 and 60 days. The bond resistance for water storage is greater than for air storage for all ages at which tests were made; the maximum bond resistance for the water-stored specimens is greater by 30% and 23% at 7 and 41 days, and 77% and 42% at 14 mo. and 26 mo. The 60-day tests show an increase over the 7-day tests of 38% for the air-stored and 53% for the water-stored specimens. The 26-mo. tests show an increase over the 60-day tests of 50% for air storage and 64% for water storage. The specimens tested at 60 days show a slightly lower bond resistance than the specimens tested at 41 days; this, however, is probably an accidental variation.

The bond resistance at beginning of end slip shows about the same relation as at the maximum loads. The high bond resistance developed in the older specimens is noteworthy. For the water-stored specimens tested at 26 mo. the bond stress at beginning of slip of the free end of the bar was 624 lb. per sq. in., and the maximum bond resistance was 950 lb. per sq. in. The bond stresses developed by the specimens from Batch 35 are somewhat lower than those from Batch 3 for the same age and storage, although the 6-in. cube tests indicate that the concrete was of about the same quality.

33. *Batch 41.*—The tests from Batch 41 were in part duplicates of those in Batch 35. Four sets of specimens were placed in water during the first half of their storage period and in air for the remainder of the time. In this group the water-stored specimens gave a higher bond resistance at all stages of the tests than the air-stored. At 31 days the sand-stored specimens were stronger than the water-stored, while at 60 days the reverse was true. The highest values for bond on plain bars from the tests reported in this bulletin were found in the

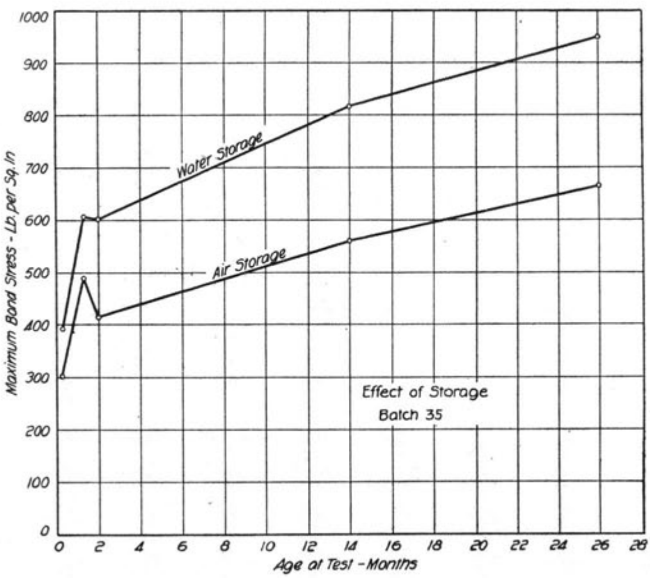


FIG. 20. MAXIMUM BOND RESISTANCE FOR SPECIMENS STORED IN AIR AND IN WATER.

tests of the sand-stored specimens in this series, which were tested at 14 mo.; the maximum bond stress of 1060 lb. per sq. in. from these tests corresponds to a steel stress of 31 400 lb. per sq. in. in the 1-in. bar which was embedded only 8 in.

The specimens stored 4 days in water and 3 in air gave about the same values as those stored in air for 7 days. Those stored 14 days in water and 17 days in air gave a somewhat lower maximum bond resistance than those stored 31 days in air. The specimens stored 30 days in water and 30 days in air gave values between the water and air stored specimens tested at 60 days. The specimens stored 3 mo. in water and 11 mo. in air gave values between the sand-stored and the air-stored specimens tested at 14 mo. In general these tests show a progressive increase of bond strength with age for all conditions of storage. The values at the older ages for all conditions of storage are high.

34. *Batch 39.*—In order to study the effect of storing specimens for a period in water followed by varying periods of air storage tests were made as given under Batch 39 in Table 12. The specimens stored in water 61 days were tested immediately upon removal from the water and were thoroughly wet when the load was applied. These tests indicate that the drying-out of the water-stored specimens before testing has an influence in increasing the bond resistance, although the evidence is not entirely conclusive.

35. *Discussion of Effect of Storage.*—The tests in Table 12 show about the same bond resistance for damp-sand storage as for water storage for ages up to 60 days; and the high stresses developed by the specimens in Batch 41 stored in damp sand for 14 mo. indicate that this relation may be expected to hold indefinitely unless affected by other agencies. The water-stored specimens gave from 10% to 45% higher bond resistance than the corresponding air-stored specimens, an average of 26% for 13 parallel sets of tests, based on the maximum bond stresses given in Table 12. This difference seems to increase with age; three parallel sets of tests made after 1 year show an average increase in bond resistance of 37% in favor of the water-stored concrete. The compression tests on 6-in. cubes show an average excess of strength of 25% for the water-stored specimens over the air-stored specimens. Since sufficient water was used in mixing the concrete, it is probable that evaporation of water from the concrete was the cause of the lower bond resistance in the air-stored specimens.

The presence of water not only does not injure the bond between the concrete and steel for ages up to 3 years, but it is an important factor in producing conditions which result in high bond resistance. Conditions of stress in concrete under load may modify these results, but it seems likely that the relative bond resistances in service will not be materially different from those found in the above tests with concrete of the same quality and with similar exposure.

d. Bond Tests with Deformed Bars.

36. *Preliminary.*—The term "deformed bar" is applied to a form of bar with projections on the surface or other frequent irregularities of section and designed and rolled specially for concrete reinforcement. These irregularities of section or projections are expected to increase the bond resistance of the bar. Some hundreds of patents have been issued on bars of this kind, but only a few forms have been used to any extent. Present building codes and engineering specifications generally permit the use of higher bond stresses in the design of structures in which deformed bars are to be used than are permitted in the case of plain bars.

In the 1909 series, pull-out tests were made with seven commercial types of deformed bars, which number included most of the types of deformed bar in use at the time the tests were begun. Fig. 21 shows the forms of the bars used, and Table 13 gives the characteristics of these bars. For comparison, tests on specimens with plain round, twisted square, and threaded round bars were included. The size of the bars varied from $\frac{1}{2}$ to $1\frac{1}{8}$ in. The concrete cylinders were 8 in. in diameter with 8-in. embedment. The concrete was 1-2-4, hand-mixed. All specimens were stored in damp sand and tested at the age of about 2 months. In general, the tests were made in sets of five, one specimen of each kind having been made from each of five batches of concrete. A period of about 2 months elapsed between the making of the first and the last specimens. In all the specimens except those with plain round bars the concrete cylinders were reinforced against splitting by means of a wire spiral, since the load-slip relation was desired rather than values for ultimate strength. A summary of the average values from the tests is given in Table 14. The load-slip curves are plotted in Fig. 23 and 24.

Deformed bars were used in several other groups of pull-out tests which are not included in the present discussion. Tests with deformed bars in which the concrete blocks were not reinforced against splitting are discussed in Art. 64.

37. *Phenomena of Pull-out Tests with Deformed Bars.*—In the discussion of bond on plain bars it was seen that the adhesion between the concrete and steel was broken by a very small movement of the bar and as movement continued the bond was gradually taken by sliding resistance, which resulted from inequalities of the surface of the bar and from irregularities of its section and alignment. The projections on a

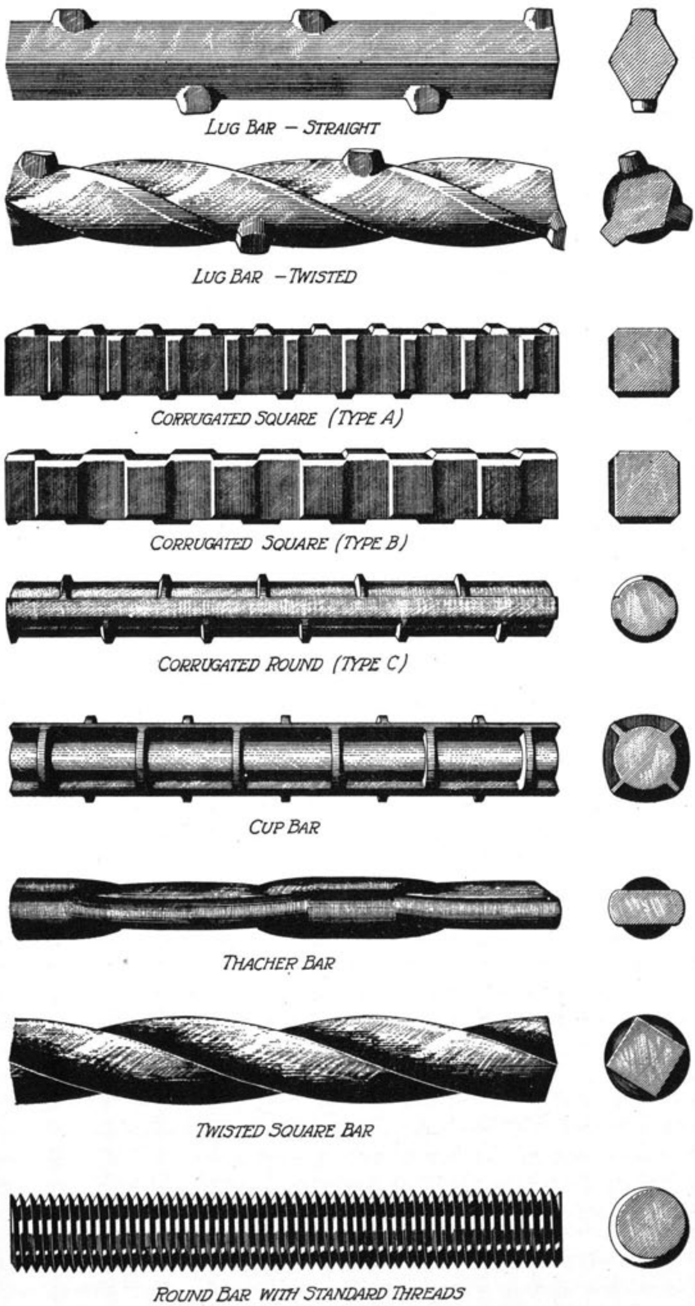


FIG. 21. DEFORMED BARS USED IN PULL-OUT TESTS.

deformed bar give an exaggerated case of inequality of surface and irregularity of section. The tests described below indicate that the projections do not assist in resisting a force tending to withdraw the bar until a slip of bar has occurred approximating that corresponding to the maximum sliding resistance of plain bars. The sliding resistance of plain bars reaches its maximum value at a slip of about 0.01 in. It

TABLE 13.

Notes on Deformed Bars Used in 1909 Pull-out Tests.

The forms of these bars are shown in Fig. 21.

Bar	Equivalent Section	Perimeter,* inches	Remarks
½-in. twisted lug bar°	Hexagonal in section,	1.87	Lugs 2.4 in. apart; 2.7 twists per ft.
⅝-in. twisted lug bar°	equivalent to square	2.32	Lugs 2.4 in. apart; 2.0 twists per ft.
¾-in. twisted lug bar°	bar of same nominal	2.78	Lugs 2.4 in. apart; 1.7 twists per ft.
1 -in. twisted lug bar°	size.	3.78	Lugs 2.4 in. apart; 1.0 twists per ft.
½-in. cup bar	Round bar, equivalent	1.77	Cups 1 in. long.
¾-in. cup bar	to square bar of same	2.65	Cups 1⅛ in. long.
1 -in. cup bar	nominal size.	3.56	Cups 1¼ in. long.
½-in. Corrugated sq. Type A	Square bar having the	1.32	Corrugations .06 in. high 0.5 in. apart on all faces.
¾-in. Corrugated sq. Type A	perimeter shown.	2.50	Corrugations .08 in. high 0.7 in. apart on all faces.
1 -in. Corrugated sq. Type A		3.56	Corrugations .09 in. high 0.9 in. apart on all faces.
½-in. Corrugated sq. Type B	Square bar of same size	2.00	Corrugations .06 in. high ¾ in. apart on all faces.
¾-in. Corrugated sq. Type B	Square bar of same size	3.00	Corrugations .09 in. high 1⅛ in. apart on all faces.
1 -in. Corrugated sq. Type B	Square bar of same size	4.00	Corrugations .11 in. high 1½ in. apart on all faces.
$\frac{9}{16}$-in. Corrugated round Type C	Round bar	1.77	Circumferential corrugations 0.05 in. high, ⅞-in. apart.
1⅛-in. Corrugated round Type C	Round bar	3.34	Circumferential corrugations 0.09 in. high, 1.6 in. apart.
¾-in Thacher	¾-in. round bar	2.35	Plain round bar flattened at intervals.
½-in. sq. twisted	½ in. square	2.00	Cold twisted; 2 twists per lineal foot.
1 -in. sq. twisted	1 in. square	4.00	Cold twisted; 1 twist per lineal foot.
1-in. round bar, threaded	Round, diameter 0.89 in.	2.80	Standard V-shaped threads, 8 per inch.

° The straight lug bars were like those given in the table, except for the twisting.

* The perimeters given are those of bars of the same weight and having the form of section indicated in the second column.

will be shown in Art. 51, in the discussion of tests on bars anchored by means of nuts and washers, that with the large bearing area present a distinct movement of the bar was necessary to bring this anchorage into action. This makes it clear that the adhesive resistance must be detroyed and sliding resistance largely overcome and that the concrete ahead of the projections must undergo an appreciable compression before the projections become effective. The action of anchored and deformed bars during the first stage of the tests does not differ much from that of plain bars. This conclusion might have been reached from our knowledge of the behavior of elastic bodies, but it is one which generally has been overlooked in discussions of the action of deformed bars.

After the adhesion is overcome and the sliding resistance of the smoother portions of the bar reaches its maximum value, the projections become effective and we may recognize a third stage in a pull-out test of a deformed bar in which the bond stress arises principally from the bearing stress between the projections and the concrete ahead. As slip continues, a larger and larger portion of the stress is taken in direct bearing. This bearing stress is opposed by a shearing stress over an area of concrete enveloping the projections. The exact stage of the test at which the projections become effective in taking stress and the amount of stress which finally may be taken in this way, depend, of course, on the design of the bar. The influence of the form of the bar and the secondary stresses developed in the concrete by deformed bars of different types are discussed in Art. 42.

Due to the elongation of the bar and to the yielding of the concrete ahead of the projections it is evident that the three stages mentioned above (adhesion, sliding resistance and bearing resistance) may be co-existent over a comparatively short embedded length of a deformed bar. In other words, the transition from the condition in which practically all the bond stress is taken by adhesion, only a little by sliding resistance and none by bearing, to that in which none is taken by adhesion, only a little by sliding resistance and practically all by bearing, is so gradual that we may not expect to find a sharp line of demarkation between them, but that the load-slip relation for deformed bars will be a continuous curve, as long as the concrete is intact.

Fig. 22 gives a typical load-slip curve for deformed bars. This curve is a composite from 55 tests, including all the tests given in Table 14 on bars of ¾ in. and larger sizes, except the plain round, twisted square and threaded bars. The twisted square and threaded bars are not considered in the present discussion of deformed bars.

The bond stresses for various amounts of end slip are given as percentages of the average bond stress which was developed at an end slip of 0.1 in. Since the value used for the highest bond resistance considered is purely arbitrary, it will be seen that the percentages given in Fig. 22 are only relative. However, the curve plotted in this form is useful in showing the relation of bond resistance to end slip of bar. It would have made little difference in the relative position of the curve if the average bond resistance corresponding to an end slip of, say, 0.05 in. or 0.2 in. had been used as 100%. End slip of bar began at about one-third the stress corresponding to an end slip of 0.1 in. After slipping began, the increase in bond resistance was nearly proportional to the amount of slip up to an end slip of about 0.01 in. After an end slip of 0.05 in. the bond resistance increased very slowly with further withdrawal of the bar. It should be borne in mind that

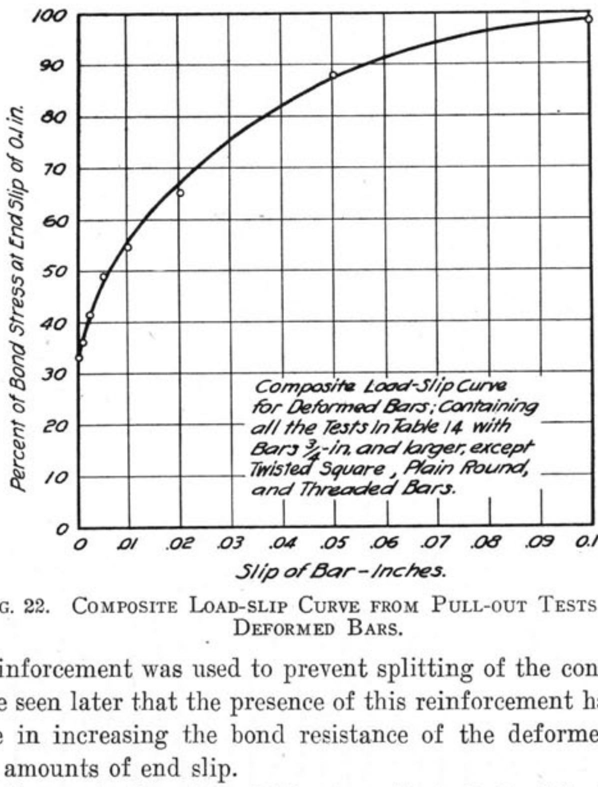


FIG. 22. COMPOSITE LOAD-SLIP CURVE FROM PULL-OUT TESTS WITH DEFORMED BARS.

spiral reinforcement was used to prevent splitting of the concrete blocks. It will be seen later that the presence of this reinforcement had a marked influence in increasing the bond resistance of the deformed bars even at small amounts of end slip.

A reference to Fig. 23 and 24, where the individual load-slip curves for these tests are plotted, will show that the form of the curves for deformed bars and their position on the diagram are not materially different from the curves for the plain bars up to an end slip of about 0.01 in., corresponding to the maximum bond resistance of the plain bars. This makes it apparent that up to this point the bond resistance of deformed bars is principally due to the same causes as in the plain bar tests, and that the projections have not appreciably come into action at this stage of the tests. All further increase in bond resistance is due entirely to the presence of the projections. The form of the load-slip curve after slip became general varied widely for bars of different types. The form assumed by any curve probably depends on the shape, size and spacing of the projections.

Some types of deformed bar developed very high bond stresses and it is apparent that the bearing stress between the concrete and the adjacent projections was abnormally high. Some notion of the importance of these stresses and their bearing on the proper design of a deformed bar which will best resist slipping through the concrete is given in Art. 42.

38. *Basis of Comparison of Bond Resistance of Deformed Bars.*—In computing the unit stresses given in Table 14 and for other tests with deformed bars, the perimeter used was that of a bar having the same sectional shape and the same weight per unit of length as the deformed bar under consideration. The perimeters given in Table 13 for these bars were determined from the weights of the bars in this way. In order to secure a uniform basis for comparison the bond stresses corresponding to given amounts of end slip will be used. Most of the deformed bars showed an increasing bond resistance even after a large amount of slip had occurred. The highest bond resistance reported for deformed bars was that corresponding to an end slip of 0.1 in., unless the maximum load came at a smaller amount of slip. A slip of 0.1 in. is very much larger than would be available or permissible in reinforced concrete construction.

It will be seen in the discussion of bond failures in beams reinforced with either plain or deformed bars that the amount of slip at the free end of the bar which may be developed before the maximum bond resistance in the beam is reached is much less than in the pull-out tests. It is evident that if we are to secure a proper criterion of the bond value of a deformed bar from the pull-out tests we must use a load which corresponds to a slip very much smaller than that at the maximum bond stress as defined above. Certain beam tests indicate that if the load which produces a slip of about 0.001 in. at the free end of the bar is repeated or maintained constant for a considerable period the beam will ultimately fail in bond at this load. This conclusion is based on tests of beams in which the longitudinal steel was not highly stressed—see Art. 90. In the case of plain round bars the pull-out tests show that the bond resistance at an end slip of 0.001 in. is about 75% of the maximum. Professor J. L. Van Ornum, Trans. Am. Soc. C. E., Vol. LVIII, 1907, p. 294, and Professor M. O. Withey, Bulletin No. 321, University of Wisconsin, have found that with plain bars a sufficient number of repetitions of a load 60 to 80% of what would be the maximum bond resistance under a load applied progressively to failure will cause bond failure in pull-out tests or in beam tests.

It will be seen also in the discussion of the beam tests that beginning of slip at the free end of the bar (slips amounting to 0.0002 in. or less) is almost simultaneous with the appearance of cracks in the outer region of the beam. This is an important reason for using for comparison bond stresses corresponding to small amounts of end slip.

These considerations show that it is the bar which longest resists beginning of slip that should be rated highest in comparison. In the following discussion of deformed bars, the bond resistance at a slip of 0.001 in. will be used as the principal basis of comparison of the bond resistance of bars of different forms. In the summary of the tests, Table 14, the relation of the bond resistance at an end slip of 0.001 in. has been given for each set of tests in terms of the resistance of plain round bars at the same slip. Similar ratios are given for the bond stresses at an end slip of 0.01 in. Mean values for 1 and 1¼-in. plain bars have been used as a basis of comparison in determining the ratios given in the table.

The high values found in the pull-out tests are much larger than would be obtained without the restraint of the spiral reinforcement. While such values may be available in the case of a bar simply anchored, it is evident that they are not available in beam or similar construction.

39. *Discussion of Deformed Bar Tests.*—The plain round bars used in this group of tests were of high-carbon steel with ordinary mill surface. The values of bond resistance found for the plain rounds are about the same as found in other groups of tests on plain bars. The average values for the two sizes of bar are 306 lb. per sq. in. for an end slip of 0.001 in. and 405 lb. per sq. in. for the maximum bond resistance. The blocks with plain round bars were not reinforced against bursting.

Using the above values from the plain bar tests as a basis, we may make some interesting comparisons. At an end slip of 0.001 in. the 12 sets of deformed bars of ¾-in. and larger sizes in Table 14 (the 55 tests which were used in plotting the curve in Fig. 22) developed an average bond resistance of 318 lb. per sq. in., or an average of 4% more than the plain rounds at the same end slip. At this stage of the tests, two sets of deformed bars gave practically the same bond resistance, five sets gave lower values, and five sets higher values than the plain bars. At an end slip of 0.01 in., corresponding to the maximum bond resistance of plain bars, the average bond resistance of the 12 sets of deformed bars was 445 lb. per sq. in., or 10% higher than the plain bars. At this stage, two sets gave about the same resistance, two sets gave lower values and eight sets gave higher values than the plain bars. The highest value (2 tests) was about 45% in excess of the plain bars; the average of the three next highest sets was about 23% in excess of the plain bars.

In the following discussion, little will be said about the tests with deformed bars smaller than ¾ in., but the values may be seen in Table 14. The tests with threaded round and twisted square bars are discussed in Art. 40 and 41.

Tests were made on three types of corrugated bars—types A, B, and C. Types A and B are square bars, type C is designated as round but has an oval contour. These bars were of high-carbon steel.

At a slip of 0.001 in. with bars of type A (formerly known as corrugated square, old style) the ¾-in. size gave 89% of the bond resistance of plain bars. The 1-in. bars gave 123%. The individual tests for the ¾-in. bars show a wide variation; the values ranged from 183 to 390 lb. per sq. in. at a slip of 0.001 in., with an average of 273 lb. per sq. in. The load-slip curves follow closely the composite curve for deformed bars given in Fig. 22. Type B (formerly known as corrugated square, new style) gave a percentage of 101 for both the ¾ and the 1-in. bars; the value for bond stress at slip of 0.001 in. averaged 308 lb. per sq. in. for each of these sizes. Type C (commonly known as corrugated round) gave a bond resistance of 256 lb. per sq. in., for the 1⅛-in. bar at an end slip of 0.001 in., a value below all the other deformed bars. However, in other groups of pull-out tests and in the beam tests in which this bar has been used the comparison is more favorable. In the tests on effect of length of embedment, Table 9, the 1⅛-in. corrugated rounds give a bond resistance of 291 lb. per sq. in. at a slip of 0.001 in., as the average of four lengths of embedment, ranging from 4 to 24 in., while the 1¼-in. plain rounds for the same lengths of embedment gave 302 lb. per sq. in. The bars of type A give the highest bond resistance both at beginning of slip and at maximum load found in the tests on corrugated bars. It is shown in Art. 42 that these differences may readily be accounted for by a consideration of the details of the design of the bars. The relative values for the larger sizes of corrugated bars may be seen by reference to Figs. 23, 24 and 25.

TABLE 14.

Pull-out Tests with Deformed Bars (1909).

1-2-4 hand-mixed concrete from Batches 10, 17, 24, 27 and 30. Damp sand storage. Embedment 8 in.
All specimens except those with plain round bars were reinforced against bursting by means of 6 or 7 turns of ¼-in. wire in the form of a spiral.
The average compressive strength of 27 6-in. cubes at age of 60 days, was 1750 lb. per sq. in.
Stresses are given in pounds per square inch.

Size and Kind of Bar	Number of Tests	Age at Test	Bond Stress at End Slip of (inches)							Highest Bond Stress Considered*	Per cent at End Slip of 0.001 in.✚	Per cent at End Slip of 0.01 in.✚
		days	.0005	.001	.002	.005	.01	.02	.05			
1-in. plain round	5	73	268	301	328	362	380	356	303	380	100	100
1¼-in. plain round	9	70	272	311	352	401	418	390	317	418		
½-in. cup	5	76	396	425	453	497	545	631	828	891	139	134
¾-in. cup	5	70	321	347	367	413	468	583	935	1146	113	116
1-in. cup	5	73	290	323	365	426	504	630	916	1084	106	124
½-in. lug (straight)	2	63	405	454	514	598	636	702	774	774	148	157
¾-in. lug (straight)	5	69	306	332	356	415	454	521	647	760	108	112
1-in. lug (straight)	5	73	324	371	408	455	490	503	562	644	121	121
½-in. lug (twisted)	5	71	365	399	476	586	694	833	1072	1232	130	171
⅝-in. lug (twisted)	3	62	263	291	330	425	535	655	842	1041	95	132
¾-in. lug (twisted)	5	71	239	258	278	318	369	478	684	966	84	91
1-in. lug (twisted)	5	73	251	288	326	374	403	445	556	724	94	99
½-in. corrugated square (type A)	5	76	356	398	444	540	654	797	...	903	130	161
¾-in. corrugated square (type A)	5	70	245	273	310	361	469	577	820	861	89	116
1-in. corrugated square (type A)	2	73	334	377	412	499	588	738	945	1025	123	145
½-in. corrugated square (type B)	4	73	370	401	430	495	568	677	764	814	131	140
¾-in. corrugated square (type B)	5	69	279	308	344	407	462	559	692	710	101	114
1-in. corrugated square (type B)	3	68	247	308	355	428	497	590	741	797	101	123
$\frac{9}{16}$-in. corrugated round (type C)	5	76	336	377	398	449	526	629	876	1048	123	130
1⅛-in. corrugated round (type C)	5	74	236	256	271	299	334	411	624	824	84	82
¾-in. Thacher bar	5	70	248	279	309	370	415	470	564	719	91	102
½-in. twisted square	4	75	324	341	350	363	371	337	334	421	111	92
1-in. twisted square	4	77	249	268	290	321	343	340	353	405	88	85
1-in. threaded round	10	76	545	612	636	648	679	724	734	745	200	167

* For the deformed bars the highest bond stress considered corresponds to an end slip of 0.1 in. unless a maximum was reached at a smaller amount of slip.
✚The bond resistance of deformed bars expressed in per cent of the average bond resistance of 1 and 1¼-in. plain rounds at an end slip of 0.001 in. and at an end slip of 0.01 in.

The general characteristics of the cup bar are somewhat similar to the corrugated rounds. These bars are round in section and have a sectional area equal to that of a square bar of the same nominal size. These bars were of high-carbon steel. At an end slip of 0.001 in. the 3/4-in. cup bars show an efficiency of 113% and the 1-in. bars 106%, as compared with the plain rounds. The bond resistance developed by the cup bar at an end slip of 0.1 in. was the highest developed by any of the larger sizes of deformed bars; it averaged about 1100 lb. per sq. in. for the larger bars. However, it should be remembered that the concrete blocks were reinforced against bursting.

Tests were made on two different types of lug bar—straight and twisted. They were of high-carbon steel. The amount of twist and the spacing of the lugs are shown in Table 13. The 3/4-in. straight lug bars show an efficiency of 108% and the 1-in. bars 121% as compared with the plain round bars at an end slip of 0.001 in. The 5/8-in. twisted lug bars show an efficiency of 95%, the 3/4-in. bars 84%, and the 1-in. bars 94%. Considering only the 3/4 and 1-in. bars, the values of bond resistance are from 10% to 30% higher for the straight bars than for the twisted bars. This is true for all stages of the tests except at the highest loads considered. It will be seen in the discussion of tests on square twisted bars (Art. 41) that this is a characteristic phenomenon of pull-out tests with twisted bars. It is noteworthy that at an end slip of 0.001 in. the straight lug bars had a bond resistance about 15% greater and the twisted lug bars about 10% less than plain rounds.

The Thacher bar consists of a round mild steel bar which is flattened at intervals. Only 3/4-in. bars of this type were tested. This bar gave a bond resistance of 279 lb. per sq. in. at a slip of 0.001 in., 91% of the bond resistance of plain round bars at the same slip. The average load-slip curve for this bar follows almost exactly the composite curve for the larger sizes of deformed bars as given in Fig. 22.

In Fig. 25 the significant stresses from the pull-out tests on deformed bars have been plotted in a way that shows their relative values. The heavy solid line shows to scale the bond stress at an end slip of 0.001 in., the right end of the broken line indicates the bond stress at an end slip of 0.01 in., and the open line corresponds to the bond stress at an end slip of 0.1 in., which is the highest bond stress which has been considered in the discussion of the deformed-bar tests. The bars have been arranged in the figure in the order of the stress developed at an end slip of 0.001 in. For sake of comparison the tests on threaded bars,

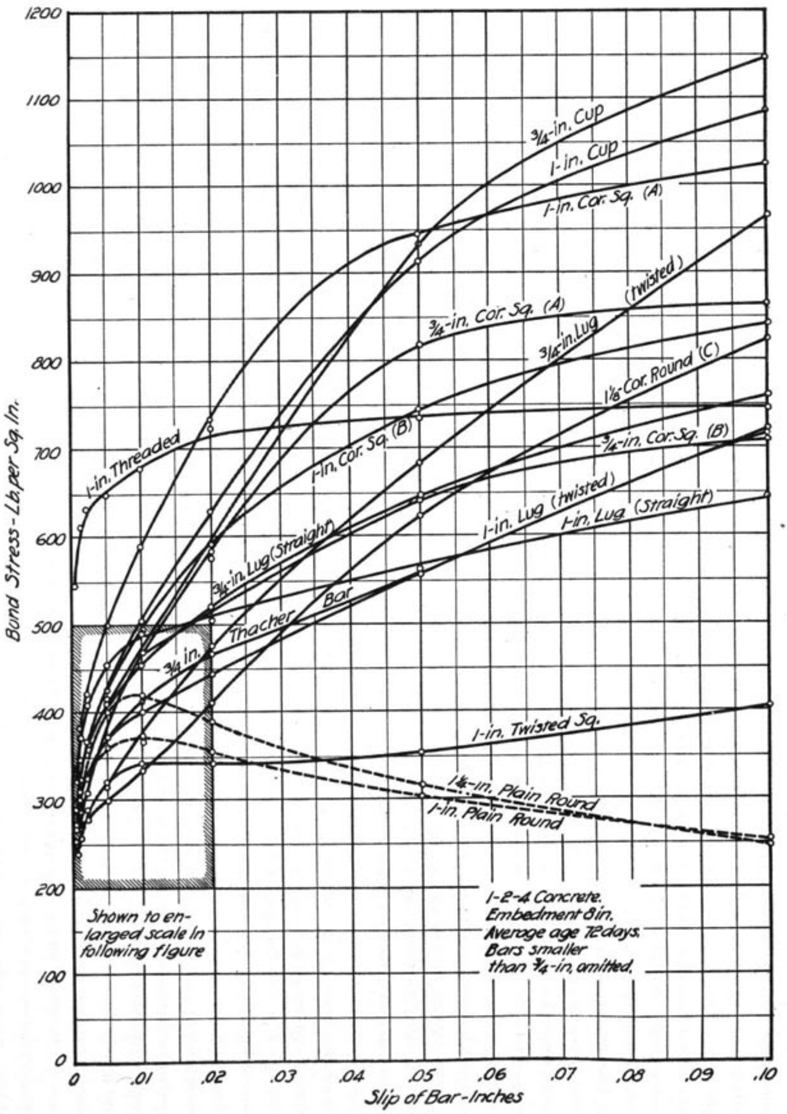


FIG. 23. LOAD-SLIP CURVES FROM PULL-OUT TESTS WITH DEFORMED BARS.

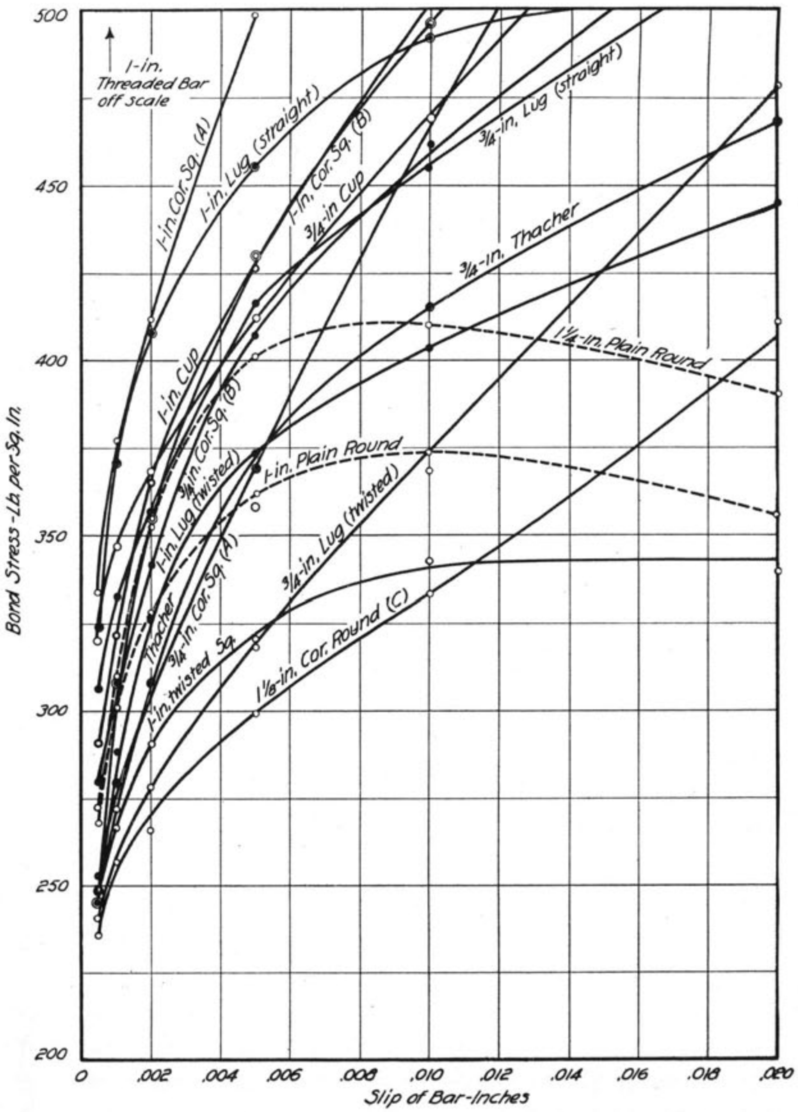


FIG. 24. LOAD-SLIP CURVES FROM PULL-OUT TESTS WITH DEFORMED BARS. (ENLARGEMENT OF A PORTION OF FIG. 23.)

twisted square and plain rounds made from the same batches have been included. The average values for the 1 and $1\frac{1}{4}$-in. plain rounds have been used. With this arrangement it is of interest to note that the plain bars occupy about a mean position, with seven commercial bars above and six below.

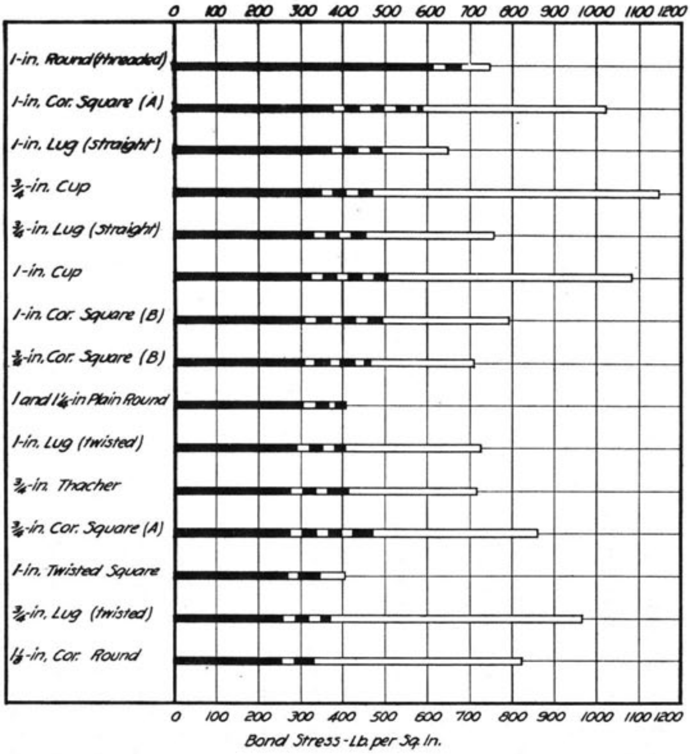


FIG. 25. RELATIVE VALUES OF BOND RESISTANCE OF DEFORMED BARS.

The heavy solid lines show to scale the bond stresses developed in the pull-out tests at an end slip of 0.001 in.; the right ends of the broken lines indicate the bond stresses at an end slip of 0.01 in.; the open lines indicate the bond stresses at an end slip of 0.10 in.

40. *Threaded Bars.*—In order to study the bond resistance of bars in which the projections were more numerous than in any of the available commercial bars, tests were made on 1-in. round bars on which a standard thread had been cut for the entire embedded length. The relation of this bar to the other deformed bars used is shown in Table 13. The results of 10 tests are given in Table 14 and the load-slip curves

in Fig. 23. This bar offers a much higher resistance to beginning of slip than any other form of bar used in these tests. The bond stress at an end slip of 0.001 in. varied from 500 to 742 lb. per sq. in.; average 612 lb. per sq. in. It will be seen that the lowest value for this bar is nearly as great as the highest for any of the commercial deformed bars of about the same size. This bar gave twice as much bond resistance as the plain round bars at a slip of 0.001 in. The maximum bond resistance came at a slip of about 0.1 in. and averaged 745 lb. per sq. in. The tests indicated that failure was produced by piecemeal shearing of the concrete surrounding the threads.

The pull-out tests on threaded bars made with the 1912 beams (see Table 34) gave somewhat lower values than those above, but the 1912 specimens were not reinforced against bursting.

41. *Twisted Square Bars.*—Pull-out tests were made on ½ and 1-in. cold twisted square bars. The characteristics of the bars may be found in Table 13. The load-slip curves for these tests have been included with the deformed bars in Fig. 23 and 24. Load-slip curves for the individual tests and for the plain rounds made from the same concrete are shown in Fig. 26. A mean curve has been drawn for each size of twisted square bars. The tests exhibit some peculiar phenomena. The load-slip curves are not unlike those for plain bars up to an end slip of about 0.01 in., except that they are lower on the scale. After a slip of about 0.01 in. has been reached there is a decided drop in the curves. This drop is found in all the curves in varying degree. It is more pronounced in the ½-in. than in the 1-in. bars. The mean curve for the 1-in. bars shows only a slight depression after a slip of 0.01 in., but the slip is increased to about 0.05 in. before there is any further increase in the bond resistance. From this point the curve continues to rise at an increasing rate. In the ½-in. bars the mean curve drops from about 373 lb. per sq. in. at a slip of 0.01 in. to 330 lb. per sq. in. at a slip of 0.04 in. and the end slip reaches about 0.10 in. before the bond resistance exceeds that corresponding to a slip of 0.01 in. After this point the course of the curve is similar to that of the 1-in. bars. The load required to pull out these bars would probably depend on the amount of restraint against the bursting of the concrete block. The maximum loads considered in the table were (as in the case of the deformed bars) those corresponding to an end slip of 0.1 in., although the load-slip curves show that a maximum point was reached at an end slip of about 0.01 in. Some of these bars were pulled out as much as

2 or 3 in. before reaching their highest resistance. The apparent bond stress at these large amounts of slip was very high, but of course such stresses and slips can not be developed in a structure, and are entirely meaningless under a rational interpretation of the tests. However, values obtained in this way have been commonly reported as the bond resistance of twisted square bars, and such tests have been generally used as the basis for the bond resistance of such bars.

The load-slip curves for twisted square bars are quite similar to those for polished bars with wedging taper given in Fig. 18. A little consideration will show the reason for this similarity and will also reveal important differences between the two cases. A longitudinal section of a twisted square bar presents an outline which consists of a series of equal arcs as shown in Fig. 26. The length of the radius and of the arcs will depend upon the amount of twist. The twisted bar is essentially a combination of a wedging taper and a non-wedging taper. As the bar begins to slip through the concrete the wedging tapers are drawn more firmly against the concrete, while at the same time the non-wedging tapers are separated from the concrete with which they were originally in contact. This separation of about one-half of the surface of the bar from its original contact is one important difference between the action of the twisted bar and that of the bar with wedging taper. Of course the separation of the surface of the twisted bars does not occur at once, on account of the curvature of the surfaces, and it may not be expected to occur as suddenly as with the polished bars on account of the difference in the texture of the surfaces. The load-slip curves for the twisted bars seem to indicate that this separation becomes pronounced at an end slip of about 0.01 in., which is about the slip at which plain bars have been found to reach their maximum bond resistance. The gradual drop in the curves suggests that the loss in bond resistance resulting from the separation of the non-wedging tapers and the continued sliding of the flatter portions of the longitudinal section have more influence in reducing the average bond resistance than the increased bearing of the wedging tapers against the concrete has in increasing the bond resistance. Continued slip of the bar finally allows the bond resistance due to the wedging action to rise and all further resistance must be due to this cause. It is evident that this action must produce a large twisting moment in the bar as well as a high splitting stress in the block. In the tests in which the bars were withdrawn, say ½ in. or more, this tendency to untwist was quite pronounced. This

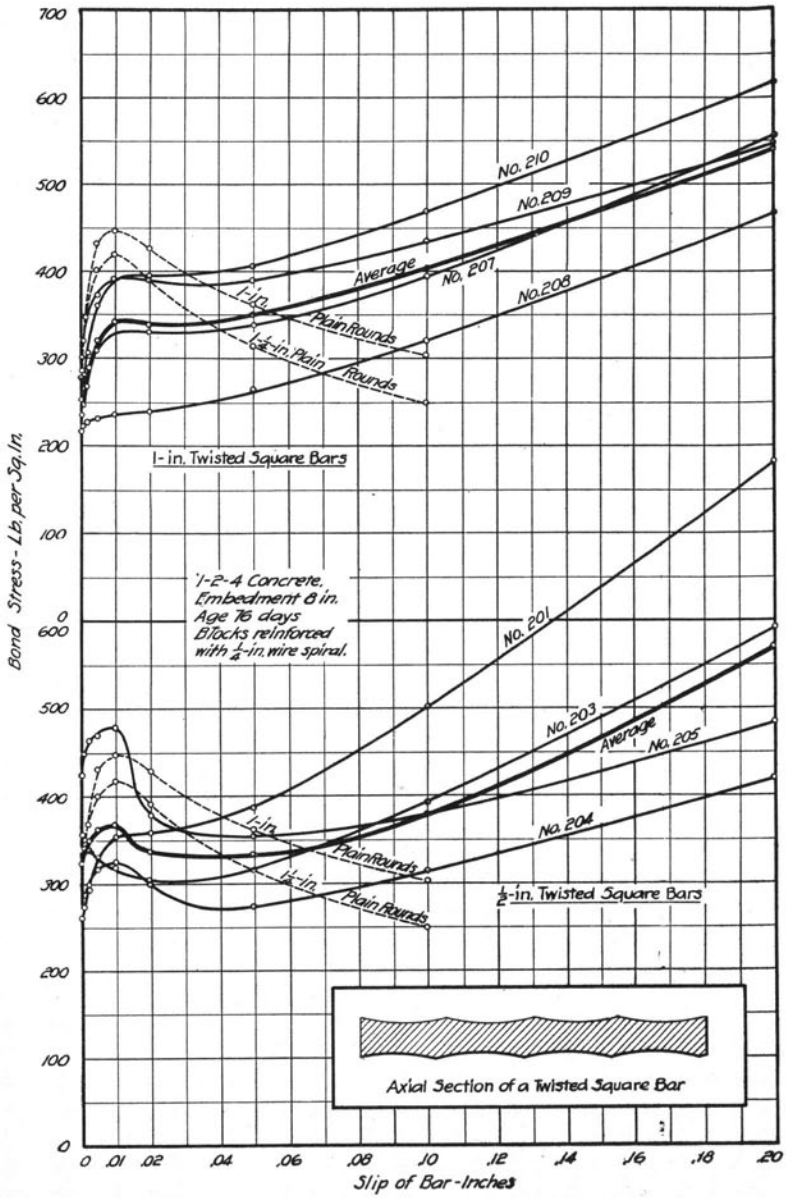


FIG. 26. LOAD-SLIP CURVES FOR TWISTED SQUARE BARS.

was shown in two ways: first, the cavity left in the top of the concrete block by the withdrawal of the bar presented the same spiral surfaces which were formed by the bar in its original position, the bar having to untwist somewhat during the movement; second, upon releasing the load at the completion of the test the blocks gave a sudden lurch in the direction of the twist in the bar. It should be borne in mind that this tendency to untwist was not pronounced until the bar had been withdrawn ½ in. or more, and that it had no effect at the loads given in the table, and may not be expected to have any influence at working stresses.

On the basis used in comparing deformed bars (the bond resistance at a slip of 0.001 in., as compared with the resistance of plain round bars) the rating of the ½-in. twisted square bars is 111% and the 1-in. bars 88%. At a slip of 0.01 in., which represents the first maximum in the load-slip curves for the twisted square bars, the bond stress for the 1-in. bars is 343 lb. per sq. in., or 80% of the value for plain rounds at the same slip. The bond stress on these bars at a slip of 0.1 in. is 93% of the maximum bond resistance for plain rounds.

It has been frequently stated that cold twisting is effective in raising the yield point of the bar by over-stressing a portion of the metal, and at the same time it furnishes a very severe test on the quality of the steel itself. However, it has been shown by tests that the elastic limit has been raised on only a portion of the section (the outside) and that for stresses above the original yield point the modulus of elasticity of the whole section is considerably smaller than the normal value for steel within the elastic limit. In other words, for stresses above the original yield point the metal in the interior of the section will be stressed beyond its elastic limit, and the rate of change in tensile deformations in the bar as a whole will be larger than at the lower stresses.

The tests here recorded show conclusively that the bond resistance of twisted square bars is inferior in characteristics to that of plain round bars of similar surface, and that these bars have little or no advantage in bond resistance within limits of slip which would be useful in structures. It seems strange that the twisted bar has gained such a wide popularity as a reinforcing material.

42. *Elements of the Bond Resistance of Deformed Bars.*—In Art. 37 and 39 the general phenomena of the tests of deformed bars were described. It seems desirable now to consider the secondary stresses which are developed in the concrete by deformed bars of the usual kind

and to learn the causes of the variations in the bond resistance of bars of different types. Such a study will indicate certain limitations of the deformed bar and furnish suggestions for the rational design of a bar which may be expected to give the best results.

We have seen that the projections do not become effective in taking bond stress until the bar has slipped an appreciable amount, and that during the later stages of the tests bond resistance is due principally to the bearing stress developed between the projections and the concrete in front of them. The pull-out tests showed that high bursting stresses were developed in the concrete blocks by the components of this bearing stress normal to the axis of the bar. This bursting action would be very destructive in a smaller mass of concrete which is under no restraint. This makes it apparent that if the bearing area of the projections is to be most effective in taking bond stress and least destructive in causing bursting, the planes of the bearing faces of the projections should be as nearly as possible at 90° to the longitudinal axis of the bar. The low bond resistance of the twisted square bar and certain deformed bars is due to the small angle which the so-called bearing faces make with the axis of the bar. In many of these tests the entire excess of bond resistance over that of plain bars was due to the restraint offered by the concrete block.

Having determined that the bearing faces should be as nearly perpendicular to the axis of the bar as practicable, the projections should be of such height and number that the proper relation between bearing stress on the concrete and shearing stress over the enveloping surface of concrete will be preserved. The ultimate bearing strength of concrete has not been studied, but these deformed-bar tests and the tests on anchored bars described in Art. 51 indicate that small areas which are restrained by a larger mass of concrete may be expected to carry a very high stress in bearing. These tests show that the concrete momentarily supported a bearing stress of from 8000 to 14 000 lb. per sq. in. Under these conditions the concrete was probably reduced to a powder as it yielded slowly under the stress.

The shearing value of concrete under these conditions has not been determined, but these deformed-bar tests show that it is higher than has commonly been assumed, and certain tests reported in Illinois Engineering Experiment Station Bulletin No. 8 indicate that it is nearly as great as the compressive strength. It may be noted that the values for the highest bond resistance given in Tables 14 and 15 were not the ultimate values of the bond resistance and that the shearing stresses finally developed over the surrounding concrete were larger than the values for bond stress which are given in the tables. However, the tests with threaded bars were the only ones in which failure occurred by shear in the concrete. In the threaded bars the bearing area was so large that the bearing stress was not great enough to produce an appreciable deformation in the concrete ahead of the threads and the elongation of the bar caused a piecemeal shearing of the concrete at an apparent stress much lower than was developed in the other tests. These considerations indicate that while high values of bearing and shearing stresses may be developed in such tests, the shearing resistance of the concrete will probably prove to be the limiting factor. The action of the threaded bars suggests that it is not desirable to keep the bearing stress too low in comparison with the shearing stress, since a slight yielding of the concrete due to a higher bearing stress will give a more uniform distribution of shearing stress and thus reduce the tendency to fail by shear. Practically all experiments in reinforced concrete in which the ultimate shearing stress was developed have emphasized the desirability of avoiding failures of this kind.

In order to study the bearing stresses developed in some of the deformed-bar tests, the values have been worked out for certain bars as shown in Table 15. The corrugated bars have been used since with the different types of bar they are instructive in making comparisons of bearing pressures, sliding resistance, and shear. For obvious reasons the lug bars and some other types could not be used in such a comparison.

It was seen above that, in general, the projections have little effect previous to an end slip of 0.01 in., and at a slip of 0.1 in. they may be considered to take all the bond stress except that taken by sliding resistance. If we consider the sliding resistance of a deformed bar to be the same as for a plain bar at the same slip, we may calculate what portion of the total bond stress is being carried by the projections at this stage of the test. It is appreciated that this method may be subject to error, since the secondary stresses in the concrete may be expected to cause an increased sliding resistance in the deformed bar, but on the other hand, this increase is probably largely counteracted by the bursting stresses developed in the concrete block. The sliding resistance of the plain bars in this series at an end slip of 0.1 in. was 250 lb. per sq. in. If we use 90% of this value, on account of the area lost by slip of bar, we may say that about 225 lb. per sq. in. of the highest bond stress of deformed bars was due to sliding resistance. The column in Table 15 headed "Bond Stress Carried by Projections at the Maximum Load Considered" shows the values obtained by subtracting 225 lb. per sq. in. from the bond stresses at an end slip of 0.1 in. for the

TABLE 15.

Bearing Stresses Developed by Deformed Bars.

Stresses are given in pounds per square inch.

Nominal Size of Bar inches.	Area of Section sq. in.	Height of Projections inches.	Spacing of Projections inches.	Area of Projections in Terms of the Area of the Bar, per cent.	Bond Stress at End Slip of		Bond Stress Carried by Projections at the Maximum Load Considered. (At End Slip of 0.1 in.)	Bearing Stress at the Maximum Load Considered. (At End Slip of 0.1 in.)	Computed Bearing Stress with a Bond Stress of 100 lb. per sq. in., all Taken by the Projections.
					0.01 in.	0.1 in.			
				Corrugated Square (Type A).					
¾	.37	.080	.700	10.7	469	861	636	5850	940
1	.70	.105	.875	11.4	588	1025	800	7000	880
1¼	1.07	.125	1.185	10.0	....	....	....	....	1000
				Corrugated Square (Type B).					
¾	.56	.078	1.10	6.0	462	710	485	8100	1660
1	1.00	.112	1.50	6.5	497	797	572	8800	1540
1¼	1.56	.114	1.75	5.5	....	....	....	....	1820
				Corrugated Round (Type C).					
¾	.44	.082	1.30	5.5	....	....	....	....	1820
1	.78	.050	1.50	2.2	....	....	....	....	4550
1⅛	.99	.087	1.60	4.2	334	824	600	14000	2400
				Round Bar with Standard V-shaped Threads.					
1	.55	.082	.125	70.0	679	745	520	740	145

bars shown. The bearing area of the projections per unit of area of the entire surface of the bar is shown in the fifth column of the table. The areas given are the areas of the normal projections of the bearing faces, without any reference to the angle at which they are placed. It will be seen that there is a wide variation in the ratio of the bearing area to the area of the surface of the bar. This value is about 11% in the type A bars, 6% in the type B bars and 2 to 5% in the type C bars; for the threaded bars the ratio is 70%. Considering that these bearing areas take all the stress in excess of that carried by adhesive resistance, the bearing stresses given in the table were computed. The bearing stresses for the corrugated bars, computed on this basis, vary from 5800 to 14 000 lb. per sq. in. The bearing stresses are seen to be inversely proportional to the bond stresses developed by these bars at an end slip of 0.01 in., when the projections were just beginning to take effect. These considerations show that the ratio of the normal projections of the bearing areas to the area of the surface of the bar is the proper criterion for judging the bond resistance of a deformed bar. The bearing stresses developed at this stage of the tests also show the absurdity of seriously considering the values that are usually reported as the bond resistance of many such bars.

The values in Table 15 also give some indication as to the proper ratio of the bearing area to the superficial area of the bar in order that the best results may be obtained. In order to obtain a notion of the bearing stress developed at ordinary bond stresses the values given in the last column of the table have been computed on the basis of a bond stress of 100 lb. per sq. in., all of which was considered to be taken in bearing by the projections. We may readily conclude that 11%, as in the type A bars, and the percentages found for the other corrugated bars are all too small, since the bearing stress is entirely too high; 70%, as in the threaded bars, is too high since the bearing stress is absurdly low and failure came by piecemeal shearing. The proper value lies between 11% and 70%; it seems probable that values of, say, 20% to 25% would give satisfactory results. Of course, a satisfactory value could readily be determined experimentally. With a ratio of 20% the bearing stress would be about four times the shearing stress over the enveloping surface if we disregard the sliding resistance; considering sliding resistance, the bearing stress would be about three times the shearing stress, which appear to be suitable values. A bar with projections extending around the circumference, practically perpendicular to the axis and having a height of, say, 1/10 of the diameter of the bar and spaced, say, ½ the diameter apart, would answer the requirements mentioned above. The spacing now ordinarily used would require so high a projection in order to secure the desired bearing area that the height would interfere with the practical requirements of manufacture and it would not give a good distribution of stress along the bar. A comparatively close spacing would give the necessary bearing area with the use of a minimum amount of metal. Advocates of deformed bars would do well to realize that a certain amount of metal must be sacrificed to the projections in a bar of proper design and to recognize the fact that if high bond resistance is desired, it must be paid for in much the same way as is done in dealing with tensile stress.

e. *Effect of Age and Mix.*

43. *Preliminary.*—To determine the effect of age and mix, several series of pull-out tests were made, using ¾-in. plain round bars and ¾-in. corrugated square bars (type B), at ages varying from 2 days to 15 months and 3½ years, with the following mixes: 1-4-8, 1-3-6, 1-2-4, 1-1½-3 and 1-1-2. These tests are summarized in Table 16. All the bars were embedded 8 in. in 8-in. cylinders of concrete; they were all stored under the same conditions and tested in the same manner. All specimens tested after 4 days were stored in damp sand upon the removal of the forms; but the storage sand was allowed to dry out after about 2 years. The blocks with corrugated bars were reinforced against bursting by means of a spiral consisting of 6 or 7 turns of ¼-in. round wire. Generally the specimens were tested in sets of 5 at each age. The specimens of each mix were made from two batches of concrete, distributed as follows: two specimens with plain rounds and three of corrugated squares for each age were made from the first batch and the remainder from the second batch. In the case of the 1-1½-3 group a part of the tests with plain round bars was duplicated. The numbers of the batches used are given in the table; for further information regarding the concrete reference may be made to Table 4.

The "Highest Bond Stress Considered" for the corrugated bars is based on the stress at an end slip of 0.1 in., if a maximum had not been reached at a smaller slip. In only a few cases was the maximum load reached before a slip of 0.1 in. had occurred.

The values given in Table 16 are the averages for the number of tests noted. For convenience of reference, the values from the compression tests of 6-in. cubes for each mix have been included. As a ready method of comparing the effect of age on each mix, the percentage of the bond stress for the several ages at an end slip of 0.01 in. to the bond stress for the same slip at age of about 60 days is given in the table. It will be seen that it would not make any material difference in the percentages given if the bond stresses developed at another slip or at the

TABLE 16.

Effect of Age and Mix.

Bars embedded in an 8 in. cylinder. Universal cement; hand-mixed concrete. Specimens tested after 4 days were stored in damp sand.
The specimens with corrugated bars were reinforced against bursting by means of 6 or 7 turns of ¼-in. wire in the form of a spiral (Fig. 1 (b)).
Stresses are given in pounds per square inch.

Concrete	Age at Test days	¾-in. Plain Round Bars								¾-in. Corrugated Square Bars										Tests of 6-in. Cubes		
		Number of Tests	Bond Stress at End Slip of (inches) 0.0005	.001	.002	.005	.01	Maximum Bond Stress	Proportional Number†	Number of Tests	Bond Stress at End Slip of (inches) 0.0005	.001	.002	.005	.01	.02	.05	Highest Bond Stress Considered*	Proportional Number†	Number of Tests	Average Crushing Strength	Proportional Number
	2	5	16	17	19	23	25	27	14	4	12	13	17	21	28	37	51	64	11	6	191	18
	4	5	28	32	36	45	45	49	26	4	17	23	29	39	53	66	87	110	22	6	271	26
1-4-8	7	5	27	32	38	47	52	54	29	5	30	35	41	56	70	85	115	133	28	6	375	36
Batches	28	5	106	120	128	139	148	149	79	5	70	97	111	138	162	198	246	273	66	6	661	63
21 and 26	65	4	124	135	150	171	183	190	100	5	109	139	158	203	246	302	365	391	100	6	1049	100
	122	3	160	172	176	179	187	210	111	5	141	159	189	232	276	343	445	470	112	6	1090	104
	15 mo.	3	233	253	285	323	364	373	196	2	269	322	379	446	500	583	689	728	203	..	....	...
	2 yr.	..	...	...	...	...	...	....	....	....	....	...	...	...	...	...	...	....	....	3	2530	241
	2	5	30	32	34	41	47	53	17	5	36	44	55	68	83	116	132	157	18	6	475	36
	4	5	37	43	52	62	69	77	25	5	69	74	88	111	134	165	213	239	30	6	641	48
1-3-6	7	5	104	112	121	145	158	165	53	5	91	104	121	148	178	211	259	286	40	6	747	56
Batches	28	5	118	130	159	206	230	241	77	5	155	179	211	269	312	363	436	462	69	6	1145	86
5 and 19	60	5	208	227	248	287	302	311	100	5	241	280	317	398	450	502	597	623	100	6	1330	100
	132	5	352	398	441	498	525	536	173	5	266	326	363	436	508	586	693	746	113	3	1640	123
	6 mo.	..	...	...	...	...	...	....	....	2	269	322	379	446	500	588	688	727	111	3	2250	169
	15 mo	3	286	333	364	372	323	372	120	..	....	...	...	...	...	...	...	....	....	..	....	...
	2	5	75	89	97	114	122	123	27	5	77	97	115	123	158	178	201	219	25	6	482	21
	4	5	97	110	131	146	152	153	34	5	108	129	145	170	196	222	271	305	31	6	726	32
	7	5	141	158	184	201	216	226	50	5	166	187	209	249	295	348	424	459	47	6	953	42
	14	5	227	247	261	278	289	300	66	5	200	216	240	290	342	401	449	477	55	6	1243	55
1-2-4	28	5	266	288	318	360	392	404	90	5	274	306	347	414	457	510	607	641	73	6	1638	73
Batches	60	5	332	363	394	432	450	452	100	5	390	434	479	559	627	682	820	854	100	6	2226	100
1 and 12	120	5	419	469	511	562	596	603	134	5	537	576	628	707	767	871	1025	1079	120	3	2323	103
	6 mo.	3	518	611	663	717	734	736	163	5	745	870	966	1070	...	...	...	1426	....	3	2370	105
	17 mo.	4	705	800	818	829	785	841‡	186	..	....	...	...	...	...	...	...	....	....	..	....	...
	2½ yr.	..	...	...	...	...	...	....	....	3	730	907	944	1080	1180	1383	...	1549‡	189	6	4330	192
	3 yr.	2	645	738	...	...	...	848‡	188	..	....	...	...	...	...	...	...	....	....	..	....	...

* Corresponding to a slip of 0.1 in. at the free end of the bar, unless the maximum load was found at a smaller amount of slip.
† The per cent of the bond resistance at an end slip of 0.01 in. as compared with that of the 60-day tests with the same mix.
‡ Bars stressed to or beyond yield point.

TABLE 16—Continued.

Effect of Age and Mix.

Concrete	Age at Test days	¾-in. Plain Round Bars								¾-in. Corrugated Square Bars										Tests of 6-in. Cubes		
		Number of Tests	Bond Stress at End Slip of (inches) 0.0005	.001	.002	.005	.01	Maximum Bond Stress	Proportional Number†	Number of Tests	Bond Stress at End Slip of (inches) 0.0005	.001	.002	.005	.01	.02	.05	Highest Bond Stress Considered *	Proportional Number†	Number of Tests	Average Crushing Strength	Proportional Number
1-1½-3 Batches 2, 13 and 33	2	8	116	123	134	150	158	159	29	5	78	92	102	118	134	154	187	205	16	6	450	16
	4	7	176	195	210	226	224	231	42	5	100	115	124	145	167	190	231	258	20	6	713	25
	7	8	241	250	262	288	296	300	55	5	132	140	144	174	193	219	783	330	24	6	1044	36
	32	8	425	457	487	527	545	546	99	5	263	281	303	341	374	402	476	560	46	6	2288	80
	62	10	451	492	508	553	554	554	100	5	446	536	606	740	818	893	...	1053+	100	6	2874	100
	120	3	484	538	585	653	663	667	120	2	474	564	640	770	894	1024	...	1070	109	3	3928	137
	14 mo.	5	768	875	892	891	875	896+	162	..	....	...	...	...	...	...	...	....	....	..	....	...
	2½ yr.	..	...	...	...	...	...	....	....	..	....	...	...	...	...	...	...	....	....	3	4583	160
	3 yr.	6	668	754	807	...	...	842	152	..	....	...	...	...	...	...	...	....	....	..	....	...
	3½ yr.	..	...	...	...	...	...	....	....	..	....	...	...	...	...	...	..	....	....	5	4804	167
1-1-2 Batches 20 and 33	2	5	99	107	118	133	141	141	27	5	87	96	104	123	145	162	202	231	17	6	490	13
	4	5	139	156	171	190	190	197	37	5	162	176	195	227	261	294	314	368	32	6	778	21
	7	4	177	202	221	240	245	246	47	5	158	171	194	238	276	314	379	419	33	6	1159	32
	28	5	272	300	328	365	378	393	74	5	313	344	383	461	537	633	750	828	65	6	2125	59
	61	5	354	399	436	498	526	530	100	5	445	498	555	678	829	989	1095	1132	100	12	3653	100
	121	2	437	479	551	613	645	666	126	3	540	599	668	776	920	1084	1142	1153	112	..	....	....
	15 mo.	3	454	656	694	738	769	779	147	2	710	892	1000	1168	1275	1405	1525	1535	136	..	....	....
	2½ yr.	..	...	...	...	...	...	....	....	..	....	...	...	...	...	...	...	....	....	3	5200	142

* Corresponding to a slip of 0.1 in. at the free end of the bar, unless the maximum load was found at a smaller amount of slip.
+ Bars stressed to or beyond the yeild point.
† The per cent of the bond resistance at an end slip of 0.01 in. as compared with that of the 60-day tests with the same mix.

maximum load were used as the basis of these values. Two groups of tests were made on mixes of the forms 1-2-m and 1-n-2n, where m varied from 0 to 8 and n from 1 to 5. The tests were made with ¾-in. plain rounds embedded 8 in. in 8-in. cylinders.

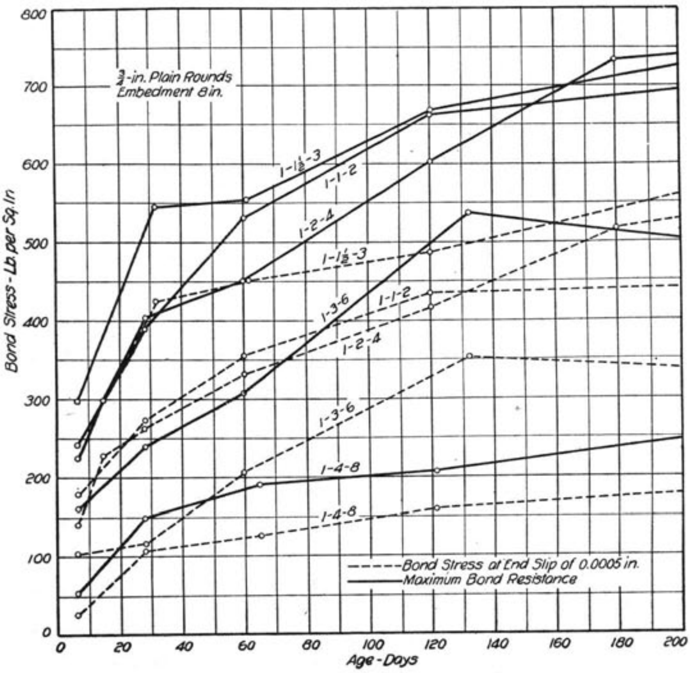


FIG. 27. EFFECT OF AGE AND MIX ON BOND RESISTANCE OF PLAIN ROUND BARS.

44. *Effect of Age on Bond Resistance.*—Fig. 27 shows the bond stresses developed in the pull-out tests with ¾-in. plain round bars with the different mixes of concrete at ages up to 6 months, at an end slip of 0.0005 in. and at the maximum. Load-slip curves for the 1-2-4 concrete at the various ages using plain bars are given in Fig. 28 and for the corrugated bars in Fig. 30. The load-slip curves for other mixes are omitted, but the values plotted for the 1-2-4 mix may be considered representative of the effect of age in the entire series.

The tests at early ages gave surprisingly high values. In the 1-2-4 concrete tests with plain bars at 2 days, slip did not become appreciable until a bond stress of 75 lb. per sq. in. was developed. The maximum bond resistance at this age was 123 lb. per sq. in—27% of the maximum at 60 days. At 4 days slip became appreciable at 97 lb. per sq. in.; maximum bond resistance 153 lb. per sq. in.—34% of the maximum at 60 days. The rate of growth of bond resistance was greatest from 2 to 7 days of age; for the older tests the rate of growth gradually became less. From 4 days to 28 days the growth in bond resist-

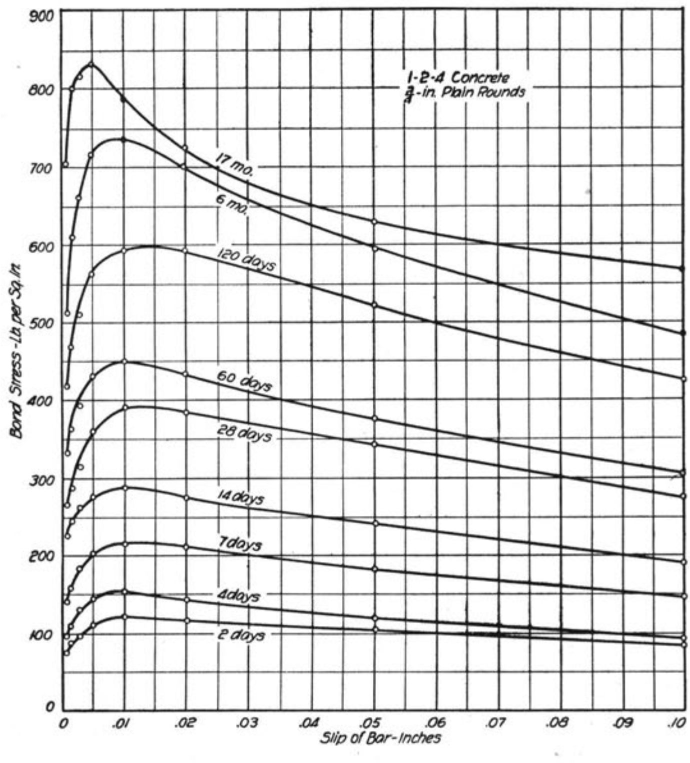


FIG. 28. LOAD-SLIP CURVES FOR PLAIN ROUND BARS EMBEDDED IN 1-2-4 CONCRETE.

ance for the various amounts of slip is nearly proportional to the age, as shown by the straight lines in Fig. 27 and 29; for 28 days to 6 months the growth in resistance is again proportional to the age. The rate of growth of bond resistance at early ages will probably depend largely on the quality of the cement used.

At 60 days slipping began in the 1-2-4 concrete at a bond stress of 332 lb. per sq. in.; the maximum bond stress at this age was 452 lb. per sq. in. These values correspond closely to those found for 1-2-4 concrete in the tests reported in University of Illinois Engineering Experiment Station Bulletin No. 8. The bond stresses developed are about the same as found in the 1912 beam and pull-out tests for 1-2-4 concrete with 1-in. plain round bars. The bond stresses at a slip of 0.001 in. for ages 120 days, 6 mo. and 17 mo. are 129%, 168% and 220%, respectively, as compared to that at age of 60 days. It seems probable that the bond resistance for small slips, such as 0.001 in., for concrete of the kind used in these tests may be expected ultimately to reach a value as much as twice that developed at 60 days.

For mixes leaner and richer than 1-2-4 the relation between the bond resistance developed and slip of bar for the plain round bars is much the same as that found with the 1-2-4 concrete. The maximum bond resistance for the plain bars was found at a slip of about 0.01 in. and the bond stress at larger slips drops off in a manner similar to that shown in Fig. 28. In all cases the bond resistance for a given end slip increased with age, except for certain irregularities at the older ages. The values in Table 16 will enable the reader to make a further study of these tests.

The tests on ¾-in. corrugated squares formed a group parallel to those with ¾-in. plain rounds discussed above. The load-slip curves for the 1-2-4 concrete are given in Fig. 29. The load-age curves for all the mixes used are given in Fig. 30. During the interval between 2 days and 7 days the bond resistance of the 1-2-4 concrete increased about 100%. From 7 days to 6 mo. there is a nearly uniform increase in bond resistance with age. During this interval the rate of growth in bond resistance is about 110 lb. per sq. in. per month, for the beginning of slip, and 175 lb. per sq. in. per month at the maximum. The values for the 1-2-4 concrete at 180 days seem abnormally high as compared with those at earlier and later ages and as compared with the other mixes. For the smaller amounts of slip at ages under 6 days the bond resistance developed by the corrugated bars is not materially different from that found in the tests of plain round bars. For an end slip of 0.001 in. in the tests at 2 to 28 days, inclusive, the corrugated bars average 8% higher than the plain rounds; for ages of 60 days and over the average is about 25% higher. As the specimens were made from the same concrete at the same time, the results give comparative values for the two forms of bar. Absolute values will vary, of course, with the concrete used. At an end slip of 0.01 in., corresponding to the maximum bond resistance of the plain round bars, the corrugated bars developed from 10% to 25% more bond resistance than the plain rounds.

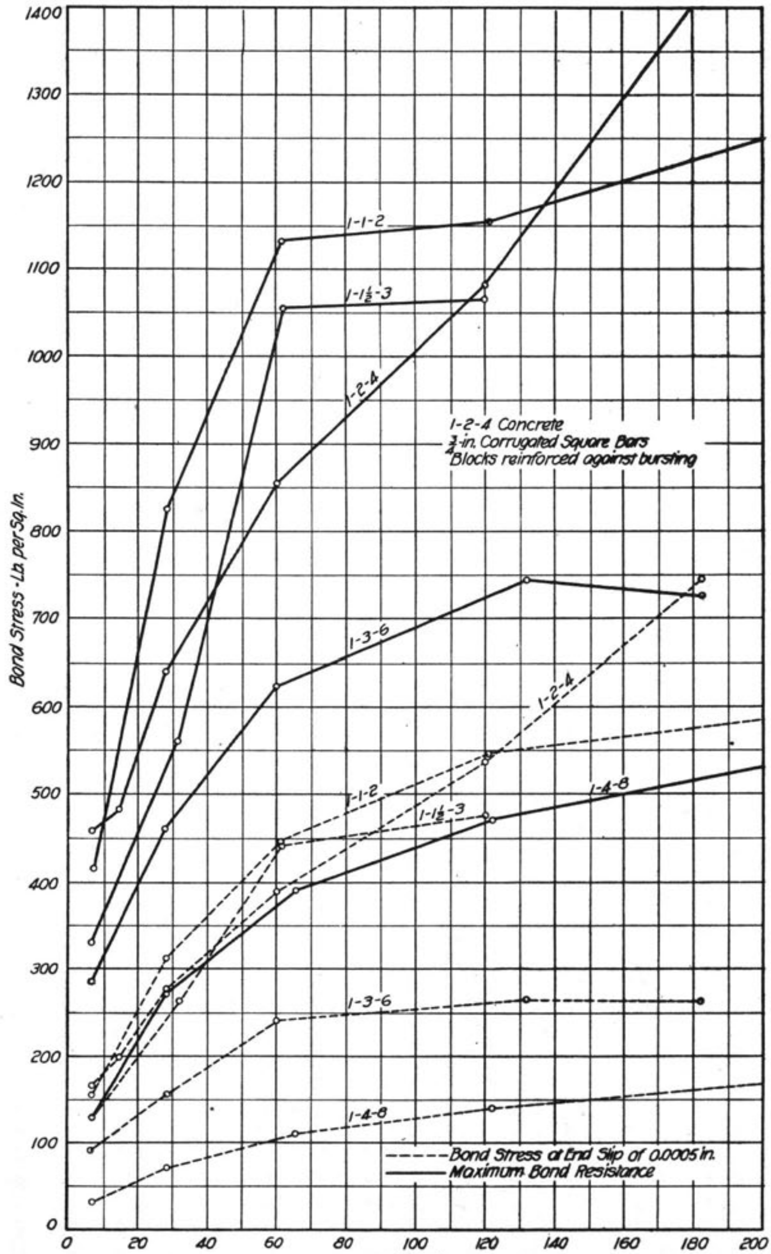


FIG. 29. EFFECT OF AGE AND MIX ON BOND RESISTANCE OF CORRUGATED BARS.

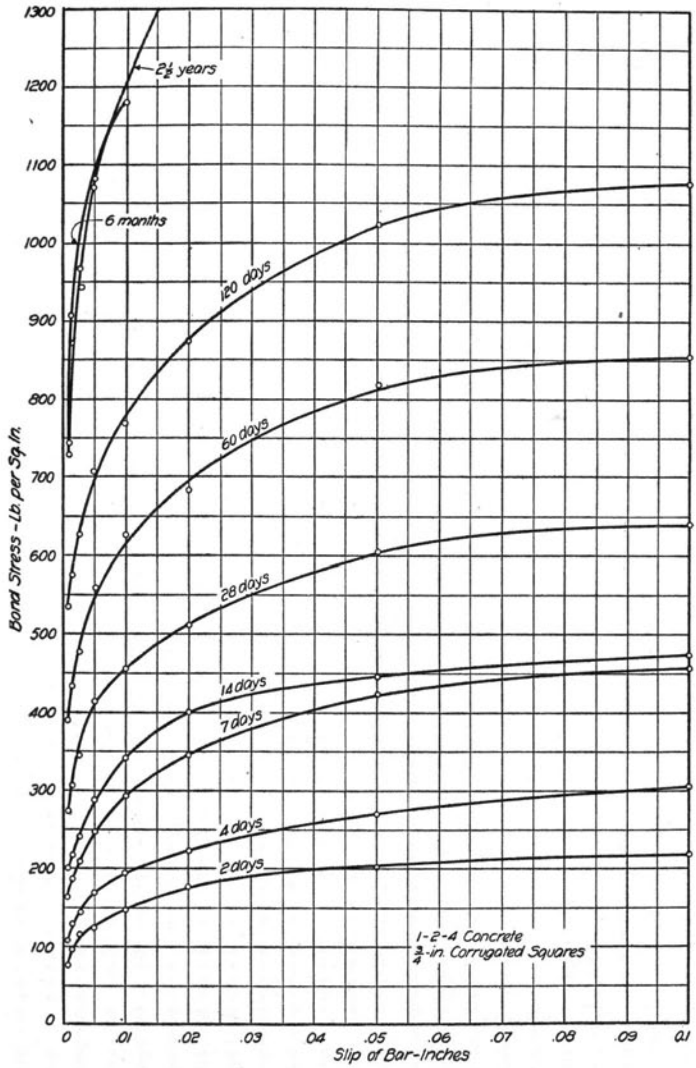


FIG. 30. LOAD-SLIP CURVES FOR CORRUGATED BARS EMBEDDED IN 1-2-4 CONCRETE.

With 1-4-8 concrete, for the smaller amounts of slip, the corrugated squares give lower values than the plain rounds for all ages under 15 months. This is true for slips up to and including 0.001 in., and in case of the 2 and 28 day tests the values for corrugated bars were lower until a slip of nearly 0.01 in. was produced, a slip corresponding to the maximum bond resistance of the plain rounds. The bond resistance for the 15-month tests is about twice that of the 60-day tests.

TABLE 17.

Comparative Values for Bond on Plain Round Bars.

Compiled from the pull-out tests with ¾-in. plain rounds given in Table 16.

The values in each of the two principal divisions of the table are given as percentages of the corresponding value for the 60-day tests with 1-2-4 concrete.

Age at Test	At End Slip of 0.001 in.					At Maximum Bond Resistance				
	1-4-8	1-3-6	1-2-4	1-1½-3	1-1-2	1-4-8	1-3-6	1-2-4	1-1½-3	1-1-2
2 days	5	9	25	34	29	6	12	27	35	31
4 days	9	12	30	54	43	11	17	34	51	44
7 days	9	31	44	69	56	12	37	50	67	55
14 days	..	..	68	...	...	...	...	66	...	...
28 days	33	36	80	126	82	33	53	90	121	87
60 days	37	63	100	135	110	42	69	100	123	118
4 mo.	47	110	129	148	132	47	119	134	148	148
6 mo.	..	...	168	...	...	..	...	163	...	...
13 to 17 mo.	70	92	220	241	181	83	83	186	...	177
2 to 3½ yrs.	..	...	204	222	...	..	...	188	198	...

With 1-3-6 concrete, the values of bond resistance for the corrugated bars at a slip of 0.001 in. average about 25% higher than for the plain rounds at the same slip.

With 1-1½-3 concrete at ages 32 days and less the corrugated bars must slip 0.05 in. or more to develop the same bond unit stress as is developed by the corresponding plain rounds at a slip of about 0.01 in. For the 62-day and older tests slip began at about the same unit stresses in the two forms of bars.

The relative values of bond resistance of plain bars for the different ages and mixes at an end slip of 0.001 in. and at the maximum are given in Table 17.

45. *Effect of Mix on Bond Resistance.*—In Table 16 the comparative values of bond resistance at a slip of 0.001 in. and at the maximum for ¾-in. plain round bars and ¾-in. corrugated square bars are given for five mixes of concrete. In computing the proportional numbers in each of the two divisions of the table, the bond resistance for 1-2-4 concrete tested at 60 days has been taken as 100%. At 2 days and 7 days the leaner mixes show bond resistances relatively lower than the richer mixes. This is probably due to the slower hardening of the leaner mixes. The relative strength at ages of 15 months and over are about the same for the leaner as for the richer mixes. It will be noted that for all the tests on plain rounds the bond resistance at a slip of 0.1 in. is about the same as that causing beginning of slip.

Load-slip curves for plain bars embedded in concrete of different mixes, tested at about 60 days are shown in Fig. 31. The effect of mix will be further considered in the following articles.

46. *Mixes of the Form 1-2-m.*—This group included pull-out tests with eight mixes of the form 1-2-*m*, where *m* varied from 0 to 8; in other words the concrete consisted of a 1-2 mortar with varying quantities of coarse aggregate. ¾-in. plain round bars were used. The values from the tests are given in Table 18. Load-slip curves are plotted in the upper portion of Fig. 31. The relation of bond resistance to the per cent of cement in the mix is shown in the upper portion of Fig. 32. The percentage of cement is expressed in terms of the total weight of the aggregates in the batch. The values for 1-2-3 concrete seem erratic. If these values be disregarded, as indicated by the dotted lines in the figure, the adjacent points line up with the others. The maximum bond resistance varied from 341 lb. per sq. in. for the 1-2-8 concrete to 757 lb. per sq. in. for the 1-2-1 mix. We may say then that bond resistance in mixes of this kind increases roughly with the amount of cement used up to about 32% of cement. This relation does not hold when we omit the coarse aggregate, as was done in the 1-2-0 mix.

47. *Mixes of the Form 1-n-2n.*—The results of these tests are given in Table 18. The lines in the lower portion of Fig. 32 show the relation of bond resistance to per cent of cement used in the batch for various amounts of slip. While the 1-5-10 concrete gives very low values, it is seen that the bond resistance increases sensibly as a direct function of the amount of cement from the 1-5-10 to the 1-1½-3 concrete, or from about 6% to 20% of cement by weight. The values for the 1-1-2 mix do not differ much from the 1-1½-3 mix. It may be that

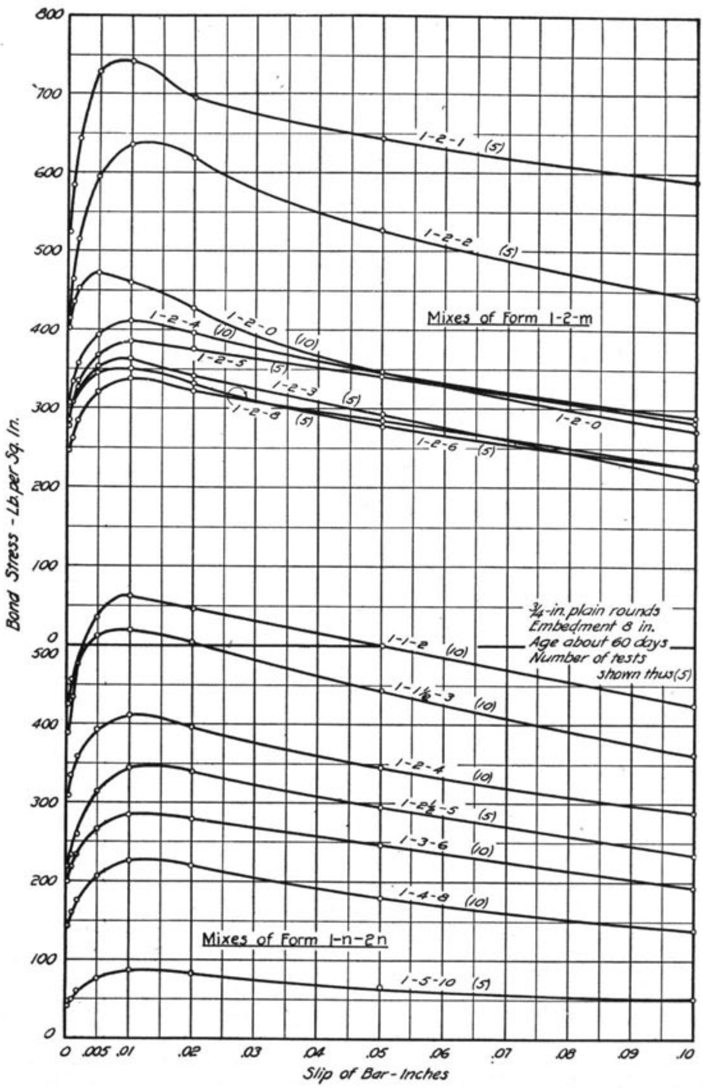


FIG. 31. LOAD-SLIP CURVES FOR PLAIN ROUND BARS.

the values for the 1-1½-3 concrete are abnormally high and those for 1-1-2 concrete somewhat low. The cube tests show a consistent relation for these mixes. However, it is evident that the general slope of these lines must decrease at the higher percentages, for it would be inconceivable for the bond resistance to continue to increase at the rate of, say, 100 lb. per sq. in. for each 5% of cement as it does for the interval between 5% and 20% in the figure. A comparison of the broken lines in the two diagrams of Fig. 32 shows that for the smaller percentages of cement the mixes of the form 1-2-*m* give somewhat higher bond resistances than those of the form 1-*n*-2*n*; but as the percentage of cement is increased (up to about 25%), the mixes of the latter form show a

TABLE 18.

Effect of Varying Quantity of Cement and Mortar.

3¾-in. plain round bars; embedment 8 in.
Hand-mixed concrete; stored in damp sand.
Stresses are given in pounds per square inch.

Mix	Batch No.	Per cent of Cement+	Age at Test days	Number of Tests	Bond Stress at an End Slip of		Maximum Bond Resistance	Test of 6-in. Cubes	
					0.0005 in.	0.001 in.		Number of Tests	Compressive Strength
Mixes of Form 1-2-m.									
1-2-0	29	41.6	72	10	435	452	472	..	....
1-2-1	18	31.3	60	5	525	584	757	3	2870
1-2-2	8	25.0	60	5	401	464	639	6	2696
1-2-3	15	23.8	61	5	284	306	367	3	1733
1-2-4°	1, 12, 24	16.3	65	10	304	333	418	12	1847
1-2-5	16	14.0	61	5	278	309	393	3	1685
1-2-6	28	11.1	65	5	277	307	355	3	1108
1-2-8	32	9.7	73	5	244	260	341	3	1240
Mixes of Form 1-n-2n.									
1-1-2°	6, 20, 23	30.5	61	10	389	433	569	12	3653
1-1, ½-3°	2, 13, 33	20.1	62	15	425	454	521	6	2874
1-2-4°	1, 12, 24	16.3	65	10	304	333	418	12	1847
1-2, ½-5	14	12.7	61	5	218	230	352	3	1555
1-3-6°	5, 19, 38	10.1	62	10	200	217	287	9	1372
1-4-8°	7, 21, 26	7.4	60	9	144	160	242	12	1102
1-5-10	9	5.9	60	5	40	49	87	6	533

+ The per cent of cement is the ratio of the weight of the cement to the combined weights of the sand and stone.

° These sets of tests result from combining the 60-day tests in Table 16 with additional sets of 5 specimens each from separate batches.

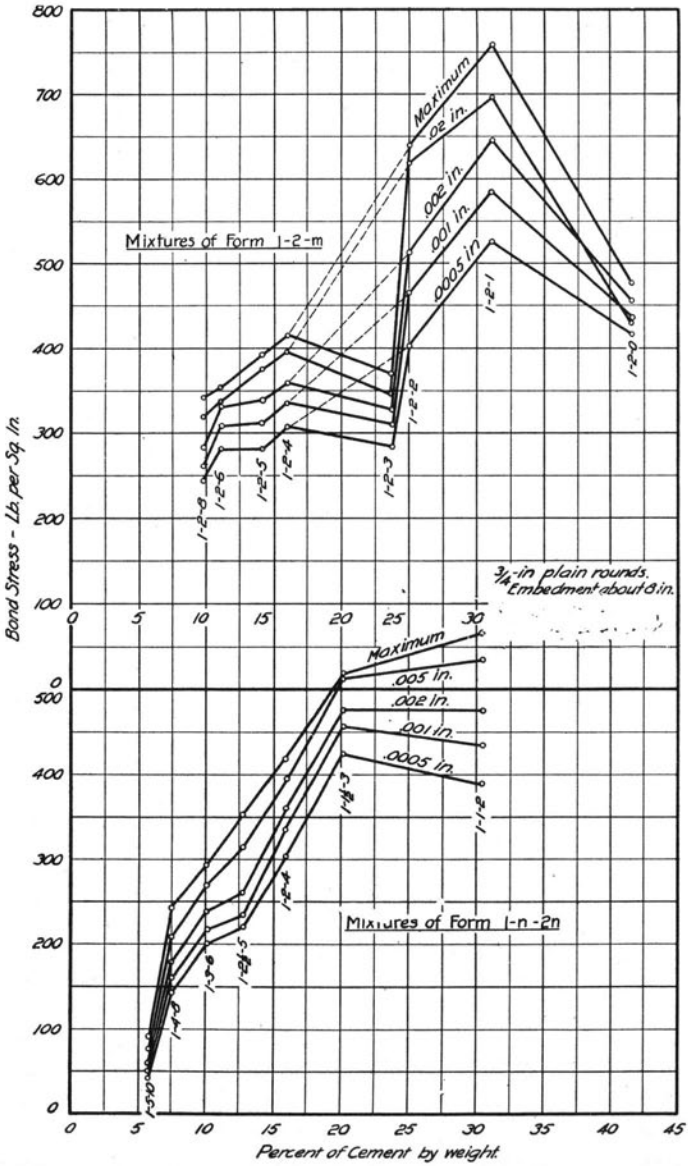


FIG. 32. BOND RESISTANCE FOR DIFFERENT MIXES.

more rapid increase. The load-slip curves given in Fig. 31 show the values of bond resistance as slipping of the bar progresses. The similarity of the curves will be noted. The values are the same as those in the group of curves given in the lower portion of Fig. 6.

48. *Relation of Bond Resistance to the Compressive Strength of Concrete.*—In Fig. 33 bond stresses corresponding to an end slip of bar of 0.0005 in. have been plotted as ordinates and the compressive strength of the corresponding 6-in. cubes have been plotted as abscissas. In Fig. 34 the maximum bond resistances have been used as ordinates. These figures include all sets of tests in Tables 12, 16 and 18, for which both values are given. The figures include tests at ages of 2 days to over 2½ years and from mixes of 1-5-10 to 1-1-2, and specimens stored

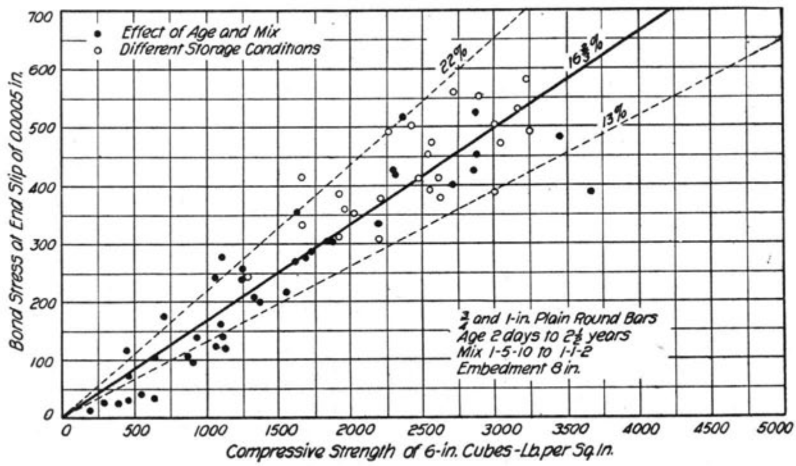


FIG. 33. RELATION OF BOND STRESS AT END SLIP OF 0.0005 IN. TO THE COMPRESSIVE STRENGTH OF 6-IN. CONCRETE CUBES.

under several different conditions. The pull-out tests were made with ¾-in. or 1-in. plain rounds embedded 8 in. Each point represents the average of from 3 to 10 pull-out tests and 3 to 12 cube tests. With a few exceptions the points fall within the regions defined by the dotted lines drawn upward and to the right from the origin. The heavy mean lines have been constructed in such a way that approximately one-half the points lie above and one-half below the lines. These figures show that end slip began in test specimens of this form at a bond stress per unit of area equal to 1/6 of the compressive strength of 6-in. cubes from the same concrete, and the maximum bond resistance is equal to about

¼ of the compressive strength of 6-in. cubes. The individual sets of tests show a variation of about 30% each way from the mean values.

49. *Effect of Age on the Compressive Strength of Concrete.*—The results of the tests on 6-in. concrete cubes made from the same concrete as the pull-out specimens are given in Table 16. These values have been plotted in Fig. 35. It will be seen that the curves for cube strength follow about the same courses as the corresponding curves for the pull-out tests with plain bars given in Fig. 27. The cube strength at 2 days is from 13% to 36% of the 60-day strength,—average 21%. The

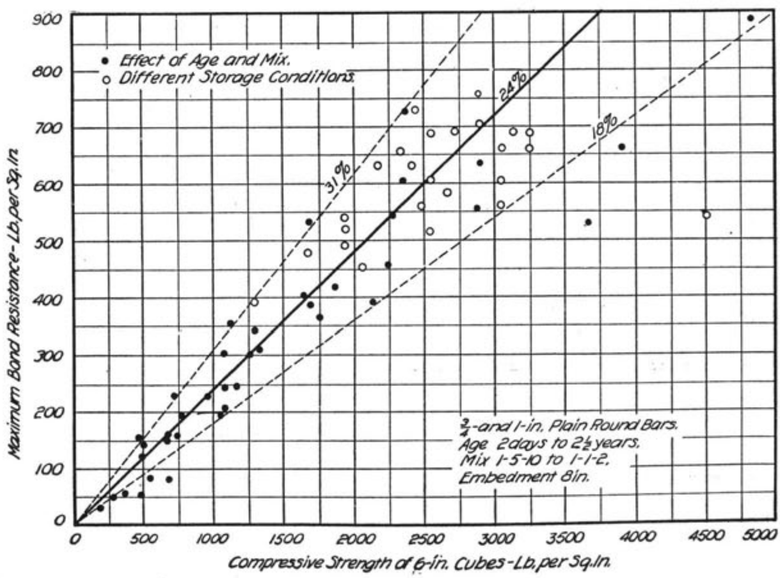


FIG. 34. RELATION OF MAXIMUM BOND RESISTANCE TO THE COMPRESSIVE STRENGTH OF 6-IN. CONCRETE CUBES.

tests made at ages of 2 to 3½ years gave values which vary from 142% to 241% of the corresponding values at 60 days; the average for 5 mixes (no tests for 1-3-6) is 193%. The lowest value of this ratio is given by the 1-1-2 concrete and the highest by the 1-4-8 mix. This indicates only that the concretes rich in cement harden more rapidly and consequently obtain a higher proportion of their ultimate compressive strength at 60 days than do the leaner mixes. We may conclude, then, that, in general, concrete made and stored under the conditions present in these tests may be expected to finally develop a compressive strength about twice that at 60 days.

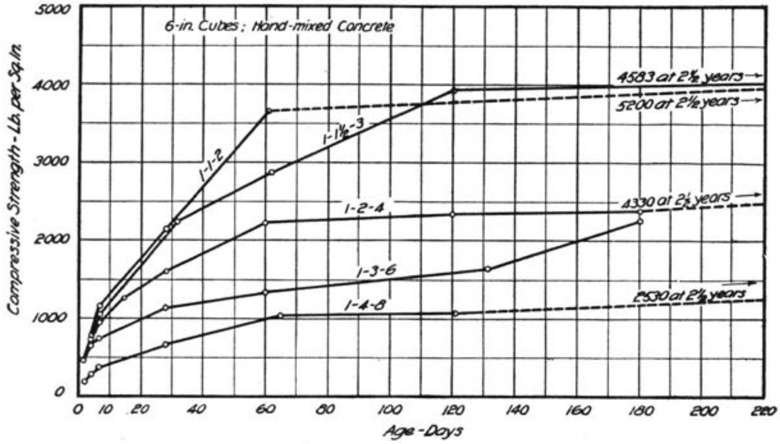


FIG. 35. EFFECT OF AGE ON THE COMPRESSIVE STRENGTH OF CONCRETE.

TABLE 19.

EFFECT OF ANCHORING ENDS OF BARS.

Embedment 8 in. 1-2-4 concrete from Batches 31, 34 and 37.
All specimens with curved or bent bars were reinforced against splitting by means of a ¼-in. wire spiral. See Fig. 36.
The average compressive strength of 6-in. cubes was 2240 lb. per sq. in.
Stresses are given in pounds per square inch.

Size of Round Bar and Manner of Anchoring	Number of Tests	Age at Test days	Bond Stress at End Slip of		Maximum Bond Resistance*
			0.0005 in.	0.001 in.	
¾-in., no anchorage	15	78	290	367	454
1-in., no anchorage	11	66	324	370	478
¾-in., anchored with nut only	5	62	292	339	925
¾-in., anchored with nuts and 2½-in. cut washer	6	75	320	373	1020
¾-in., ¼ circumference of 3-in. circle	5	69	Values for slip of bar could not be determined, since the curved or bent portions of the bars were entirely embedded in the concrete.		736
¾-in., ½ circumference of 3-in. circle	5	71			607
¾-in., 45° bend, 2 in. long	5	70			829
¾-in., 90° bend, 2 in. long	5	69			747
¾-in. 135° bend, 2 in. long	5	69			672
¾-in., 180° bend, 2 in. long	5	69			894
1-in., ¼ circumference of 3-in. circle	5	62			858
1-in., ½ circumference of 3-in. circle	5	62			653
1-in., 45° bend, 2 in. long	5	62			776
1-in., 90° bend, 2 in. long	5	62			863
1-in., 135° bend, 2 in. long	5	62			866
1-in., 180° bend, 2 in. long	5	62			1005

*** The values for maximum bond resistance for the curved and bent bars were computed by dividing the total load by the superficial area of the part of the bar embedded in the concrete, without making allowance for the load taken in direct bearing.**

f. Effect of Anchoring Ends of Bars.

50. *Preliminary.*—Many designers have sought to increase bond resistance by anchoring the ends of the reinforcing bars in beams and other members. Hooks or bends at the ends of the bars are anchorages commonly employed; nuts with washers or bearing plates are also used. It seemed desirable to supplement the information gained as to the load-slip relation in other pull-out tests with tests in which the bars were anchored at the ends. The results of these tests are given in Table 19. Four methods of anchorage were used. The forms of these specimens

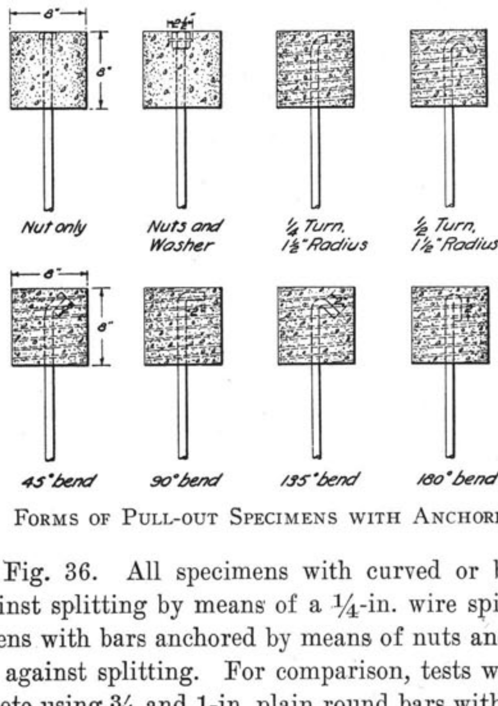


FIG. 36. FORMS OF PULL-OUT SPECIMENS WITH ANCHORED BARS.

are shown in Fig. 36. All specimens with curved or bent bars were reinforced against splitting by means of a ¼-in. wire spiral; the blocks for the specimens with bars anchored by means of nuts and washers were not reinforced against splitting. For comparison, tests were made from the same concrete using ¾ and 1-in. plain round bars without anchorage.

51. *Bars Anchored with Nuts and Washer.*—One set of tests was made using ¾-in. plain round bars having their free ends anchored by means of a standard hexagonal nut, and another set with ends anchored by means of nuts and heavy cut washers 2½ in. outside diameter. The load-slip curves for these tests and for the tests on plain bars without anchorage have been plotted to the same scale in Fig. 37. The bond stresses for the anchored bars were computed on the basis of the em-

bedded area of bar in the usual way. It was found that the bars anchored in this way gave high values of bond, but only after a considerable end slip had occurred. For the bars anchored with nuts only, slipping began at the same bond stress as in the unanchored bars, and the load-slip curves show that there was no appreciable difference in their action until

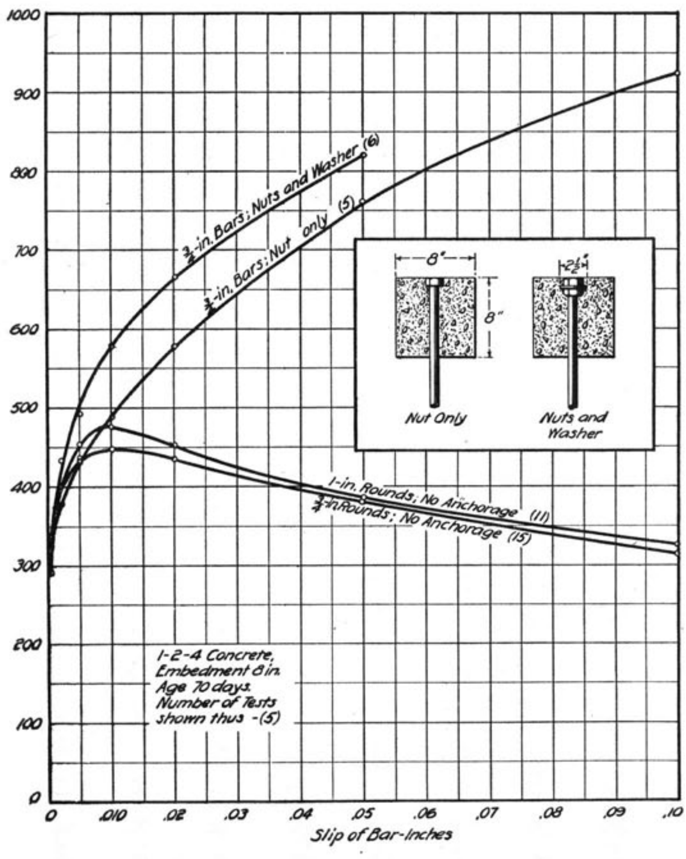


FIG. 37. LOAD-SLIP CURVES FOR BARS ANCHORED WITH NUTS AND WASHERS.

after an end slip of about 0.005 in. At an end slip of 0.01 in., corresponding to the maximum bond resistance for the bars without anchorage, the bars with nuts only showed a slight gain in bond resistance. Beyond this point the anchorage was more effective and the apparent bond stress finally reached 925 lb. per sq. in. at an end slip of 0.1 in.; the specimens failed by splitting of the blocks at a somewhat higher stress. The high bearing stress which was carried by the concrete under the nuts was a noteworthy feature of these tests, and indicates that enormous pressures may be transmitted by concrete under such restraint. If we consider that the anchored bar was developing a sliding resistance of 325 lb. per sq. in., as in the tests of bars without anchorage, we must conclude that the remaining stress was being taken by bearing on the concrete under the nut. As shown in the figure, this bearing stress must account for a bond stress of 600 lb. per sq. in. over the entire embedded area, or a total stress of 11 300 lb. This stress was taken in bearing by an area of about 0.87 sq. in., equivalent to a bearing stress of 13 000 lb. per sq. in.

The bars anchored with nuts and washers gave values much the same as the bars without anchorage up to an end slip of about 0.001 in. After this point the bond resistance increased more rapidly than in the case of bars anchored with nuts only. These specimens also failed by splitting the concrete blocks.

52. *Bars Anchored by Means of Hooks and Bends.*—Two groups of tests were made with bars anchored by means of hooks and bends, as shown in Table 19. One group consisted of ¾ and 1-in. plain rounds having the free end bent to the form of ¼ or ½ the circumference of a circle 3 in. in diameter. The other group was anchored by means of 2-in. lengths of bar bent at angles of 45°, 90°, 135° and 180° with the projected axis of the bar. The forms of these specimens are shown in Fig. 36. The specimens were reinforced against splitting by means of a spiral of ¼-in. wire as in the tests with deformed bars. In these tests, values for slip of bar could not be determined, since the curved or bent portions of the bars were entirely embedded in the concrete. The values for maximum bond resistance were computed by dividing the total load on the bar by the superficial area of the length of bar embedded in the concrete, without making any allowance for the load taken in direct bearing. The maximum bond resistance computed in this way varied from about 600 to 1000 lb. per sq. in. The bars anchored with ¼ circumference gave higher resistance than those with ½ circumferences for both sizes of bar. This is probably due to the fact that in the latter tests a larger embedded area was used in computing the unit stresses, and indicates that the added length of the hook does not have a proportional effect in resisting a load tending to withdraw the bar. As may have been expected, the bars with ¼ circumference anchorage gave results almost identical with those of the bars with 45° bends. The ¾-in. bars with different angles of bend

did not give very consistent results, but in the tests with 1-in. bars the values increase with the angle, being greatest for the 180° bend. The high resistance found for the bars with 180° bend is doubtless due to direct bearing of the end of the bar against the concrete.

53. *Discussion of Tests with Anchored Bars.*—The tests with bars anchored with nuts and washers show that movement of the bar begins at the same load as in tests with bars without anchorage. As was pointed out in the discussion of tests with deformed bars these tests show that a small movement of the bar was necessary to bring the comparatively large area of the 2½-in. washer to a bearing and the usefulness due to the adhesion and sliding resistance of the bar itself has been largely destroyed. Tests of reinforced concrete beams made at the University of Illinois (not reported in this bulletin) in which the longitudinal reinforcing bars were anchored at their ends by means of nuts and bearing plates, show that this form of anchorage has little effect in increasing the resistance of beams to web failure. It will be seen later that in tests of simple reinforced concrete beams without web reinforcement, web failures may be expected to follow immediately after the appearance of a very small amount of end slip in the longitudinal reinforcement.

In a certain sense the designers of anchorages of this kind have attempted to accomplish the impossible, since it is generally assumed that in this way slip of bar is entirely prevented, whereas a certain amount of slip is essential to bring such an anchorage into action. However, end anchorage of this form may be effective in preventing total collapse or as a safeguard against defective workmanship which results in inferior bond resistance, but it may not be expected to be effective under ordinary working conditions, since under working loads stresses which cause a general movement of the bar are not permissible. The amount of movement necessary to bring this form of anchorage into action can be minimized by proper design of the details. The use of washers or bearing plates of ample area and stiffness which are rigidly attached to the reinforcing bar will accomplish much in increasing the usefulness of this form of anchorage.

It should be pointed out that the remarks above are not intended to apply to the form of anchorage used in certain buildings, in which the longitudinal beam reinforcement is anchored to the structural members of the supporting columns by means of nuts and bearing plates and subjected to a tensile stress before the concrete is placed. In this case the beam has certain advanatages in addition to those arising from beam action.

It is impossible to interpret the tests with bars anchored by means of hooks and bends in a way that will indicate the true value of this form of anchorage. In all the tests except those with 180° bend, evidence of the straightening-out of the bars was observed at loads from 70% to 90% of the maximum. Although the blocks were reinforced against splitting, the concrete of many of the specimens was badly shattered at the maximum load. It is apparent that very high bearing and bursting stresses were produced in the concrete. The ill effects of these stresses can be reduced by the use of circular bends of longer radii than those employed in these tests.

g. Miscellaneous Tests.

54. *Preliminary.*—During the season of 1912 numerous pull-out tests were made which are of interest in indicating the influence of methods of loading which are different from that used in the tests described above and which indicate the effect of varying other details in the method of making and testing the specimens. These include the effect on bond resistance of different positions of the bar during molding, effect of distribution of load over lower face of block, effect of method of applying load in pull-out tests, double pull-out tests, repeated loads on pull-out specimens, effect of pressure during setting on bond resistance and on the compressive strength and the effect of loads reapplied after failure in bond and in compression. The results of these tests are given in Tables 20 to 24, inclusive.

55. *Repeated Load on Pull-out Specimens.*—We have seen in the foregoing discussion that it was desirable to use the bond resistance developed at a small amount of slip as the basis of comparison. This made it desirable to determine the effect of reapplying the load which caused first slip of the bar. Three tests of this kind were made on pull-out specimens. In Art. 90 similar tests on reinforced concrete beams are referred to. Fig. 38 gives the load-slip relation for a ¾-in. plain round bar embedded in 1-2-4 concrete. Load was applied until a slip of 0.001 in. was produced at the free end of the bar. It will be seen that slipping continues after this point during the time of releasing the load. At the next application the load was increased a small

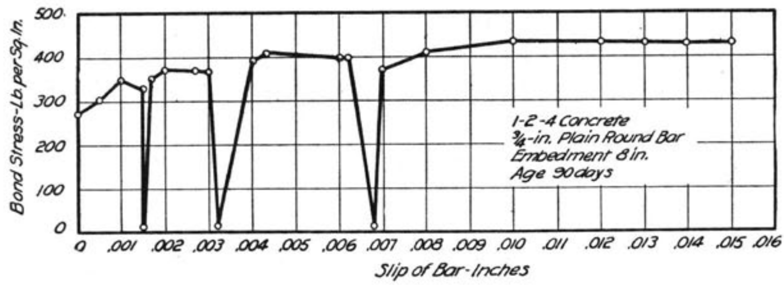


FIG. 38. LOAD-SLIP CURVE FOR REPEATED LOADS ON PULL-OUT SPECIMEN.

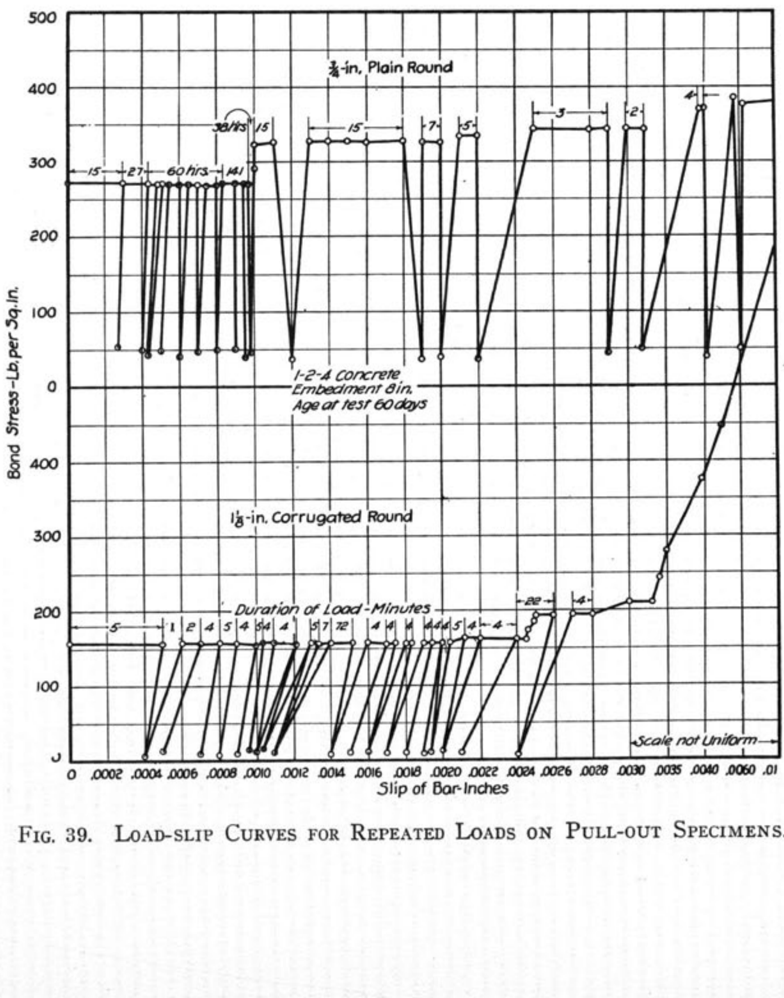


FIG. 39. LOAD-SLIP CURVES FOR REPEATED LOADS ON PULL-OUT SPECIMENS.

amount and slipping continued under constant load. The figure shows the subsequent action. The stress at a slip of 0.001 in. was 83% of the maximum bond resistance developed.

Fig. 39 shows the load-slip curves for two tests under repeated loads. The specimens were made from the same batch of concrete. In these tests the load was repeated which produced the smallest measurable amount of slip; about 0.0001 in. In the test of the ¾-in. round bar time intervals between loads are given in minutes unless otherwise noted. The slight recovery of slip upon release of load in the corru-

TABLE 20.

Miscellaneous Pull-out Tests.

1-in. plain rounds. 1-2-4 machine-mixed concrete. Age 80 days.
Embedment 8 in. unless otherwise noted.
Stresses are given in pounds per square inch.

Ref. No.	Number of Tests	Characteristics	Unit Bond Stress at End Slip of		Maximum Bond Resistance
			0.0005 in.	0.001 in.	
17	5	Bearing over entire base	280	304	364
21	6	Bearing over ring 1 in. wide as shown in Fig. 40	304	330	370
28	5	Bearing over 2½-in. circle, Fig. 40	315	336	385
45	3	Base plate adhering to block	240	268	318
49	4	Blocks directly on rubber cushion	245	267	295
53	4	Blocks cast with long end of bar upward (Fig. 1 (c))	278	315	372
57	4	Blocks cast with bars horizontal and free to settle with concrete	234	248	283
61	4	Blocks cast with bars horizontal and held rigidly in place	191	...	211
33-36	4	Specimens of form shown in Fig. 41	143	159	229
67, 68	2	Specimens of form shown in Fig. 42, embedment 12 in.	218	250	295
37*	4	Double pull-out specimens with plain bars as in Fig. 1 (d)	...	...	179
37*	4	Second test on bars which did not pull out in first test	...	...	268
41*	2	Double pull-out specimen with cold-rolled bars	...	...	79
41*	2	Second test on bars which did not pull out in first test	...	...	90

* The load was applied to these specimens through nuts at the free ends of the bars. Measurements of slip of bar were not taken. In each specimen of this form, failure in the first test was due to the pulling out of the bar which was embedded in the top portion of the specimen as it was molded. In the first tests the concrete blocks were subjected to a tensile stress. In making the second tests the specimens were set in the machine in the usual way for pull-out tests, and load applied to the bars which remained intact after the first tests.

gated bar test is noteworthy; there is no indication of such elastic recovery in the plain bar tests. These tests show that the repetition of the load which produces first slip of bar will cause a continued slipping, and if repeated a sufficient number of times would probably produce a slipping sufficient to endanger a structure. Not enough data are available upon which to base conclusions as to the values of the bond stress which may be indefinitely repeated without producing failure.

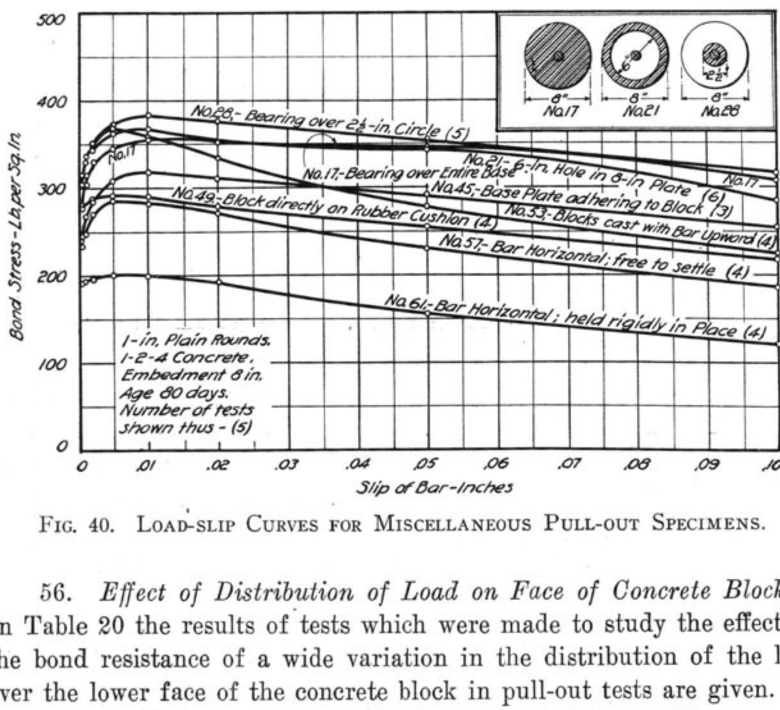


FIG. 40. LOAD-SLIP CURVES FOR MISCELLANEOUS PULL-OUT SPECIMENS.

56. *Effect of Distribution of Load on Face of Concrete Block.*—In Table 20 the results of tests which were made to study the effect on the bond resistance of a wide variation in the distribution of the load over the lower face of the concrete block in pull-out tests are given. It makes little difference whether the load is distributed uniformly over the entire base of the block or concentrated over an annular ring covering only the outer or the inner portion of the block. Whether the block rests directly on a rubber cushion or adheres to the base plate, has little effect on the bond resistance. The load-slip curves for these tests are given in Fig. 40.

57. *Effect of Position of Bar During Molding.*—In Table 20 the results of tests on pull-out specimens which were molded with the bars in different positions are given. In one set of tests the bar was supported by the form in such a way that settlement with the concrete was

prevented. Specimens were also made in which the long end of the bar was upward as the specimen was molded. Load-slip curves are given in Fig. 40. These tests show the effect of the settlement and shrinkage of concrete during the setting and hardening. For plain rounds it makes no difference whether the concrete settles in the same or in the opposite direction to that of the withdrawal of the bar. The effect on deformed bars is discussed in Art. 64. The specimens molded in a horizontal position gave distinctly lower bond resistances than those with bars vertical; and if the settlement of the bar with the concrete was entirely prevented, sliding resistance was very low and the maximum bond resistance was reduced to about 60% of that found for pull-out specimens from the same batch made with the bars in a vertical position. This shows one disadvantage of fixing the horizontal bars too rigidly in place before placing the concrete in a reinforced concrete member.

58. *Effect of Method of Applying Load in Pull-out Tests.*—Specimens of the form shown in Fig. 41 were made in order that measurements might be made on slip of bar at the point where the bar enters the concrete block, as well as at the free end. The load-slip curves for points A and B show this relation. Slipping begins at B at an average bond stress of about 70 lb. per sq. in. on the bar and reaches 0.001 in. at this point at an average stress of 136 lb. per sq. in. Slip at B reaches about 0.001 in. before slipping becomes appreciable at A. As may have been predicted, the curves indicate that slipping becomes general as soon as movement begins at A, and thereafter there is a nearly constant difference in the amount of slip measured at A and B. Part of the movement at A which, in the above statement, has been assumed to be slip at early loads, may be due largely to deformation in the lower face of the block.

Specimens of the form shown in Fig. 42 were made in order to measure the slip at several points along the embedded length. Measurements were made at points A to E at intervals of 3 in. It was desired to reproduce in a pull-out specimen the conditions of bond stress that exist near the end of a reinforced concrete beam, but the conditions in a beam were only imperfectly reproduced. The curves arrange themselves in two distinct groups. D and E show slipping to begin at a low bond stress; a much higher stress is required to produce slip at C. These specimens were made with the bar in a horizontal position; it was seen above that this has the effect of giving a lower bond resistance than was found in specimens molded with the bar vertical.

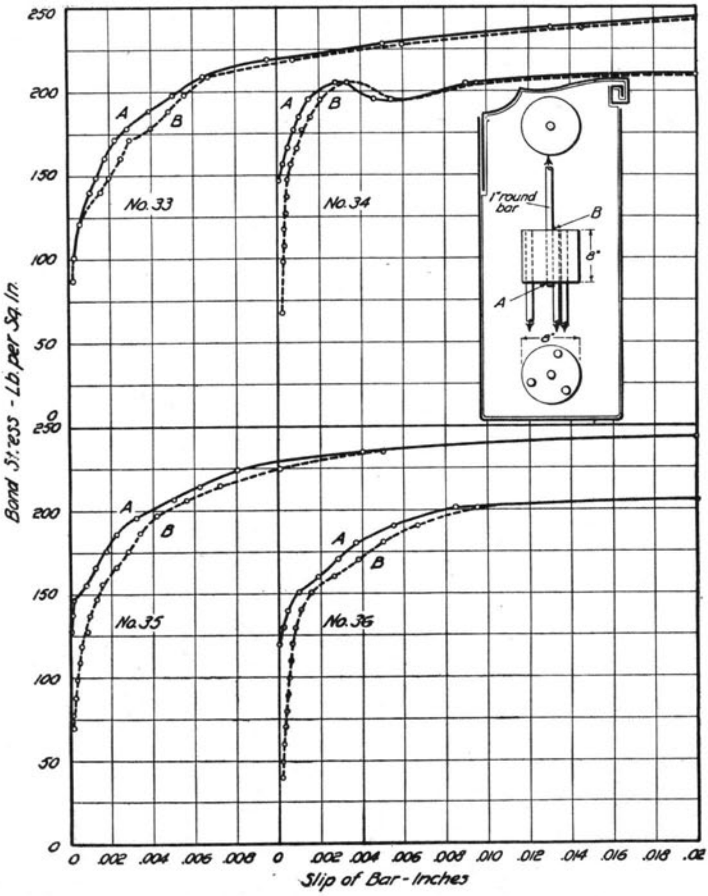


FIG. 41. LOAD-SLIP CURVES FOR SPECIMENS OF THE FORM SHOWN.

Results of double pull-out tests of the form shown in Fig. 1 (d) with ordinary round and cold-rolled bars are given in Table 20. Each bar was embedded 8 in. in a 16-in. cylinder of concrete. The maximum bond resistance in the double pull-out tests on ordinary bars was 179 lb. per sq. in., as compared with 375 for the usual pull-out specimens. It is of interest to note that in all the double pull-out tests the bar which was embedded in the upper portion of the cylinder was the one to pull out in the first test. The bar which did not pull out in the first test was later pulled out by supporting the block in the testing machine in the usual way for pull-out tests. The higher bond resistance given by the lower bar may be due in a measure to the concrete being protected against drying-out, as well as to the influence of the slight pressure under which setting occurred. The difference between the values for the first and second tests may be expected to show the influence of the different conditions of loading, but the entire difference in bond resistance cannot be attributed to this cause, since the bar with the lower bond resistance would be the one to pull out in the first test.

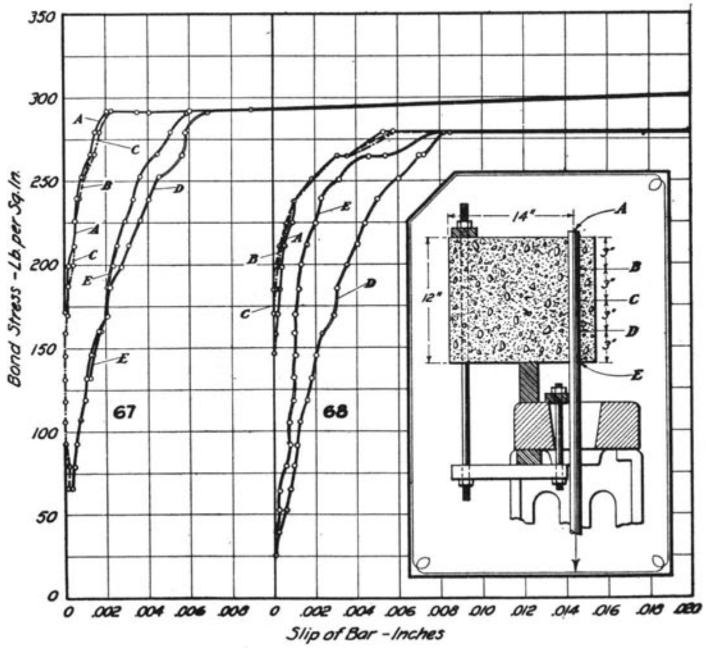


FIG. 42. LOAD-SLIP CURVES FOR SPECIMENS OF THE FORM SHOWN.

59. *Autogenous Healing in Concrete.*—The term "autogenous healing" may be applied to an interesting group of phenomena which were brought out in the tests on pull-out specimens loaded one or more times after having been previously tested to their maximum resistance, and in the compression tests on concrete cylinders which had been loaded to failure at an earlier age. These tests were suggested by certain observations made by the writer during the summer of 1911, while con-

ducting a load test on a 40-ft. through girder reinforced concrete bridge for the Illinois Highway Commission.* This test bridge was built by convict labor in December, 1907, inside the prison yard at the Southern Illinois Penitentiary near Chester, under the direction of Mr. A. N. Johnson, State Highway Engineer. In May, 1908, a test load amounting to 106 tons was placed on the bridge floor and removed. This load was sufficient to cause numerous diagonal tension cracks in the web near the ends of the girders. These cracks were very minute and were not observed until subsequent weathering brought them out. Before beginning the 1911 test all such cracks were carefully mapped, and the girders whitewashed. At this time crushed stone and pig iron were piled on the bridge floor and on the girders sufficient to give a live load of 309 tons on one girder. During the progress of the loading, some of the original cracks re-opened at loads much higher than that applied in the first test. Many of the original cracks, however, did not re-open under the final load, although new cracks sometimes formed in the immediate vicinity. The bridge was about four months old when first loaded, but it is probable that the concrete strength was not greater than would have been found at, say, two months, under more favorable temperature conditions. The behavior of the girders could be partially accounted for in the increased strength and stiffness of the concrete acquired during a period of more than three years since the first test; but this would scarcely account for the concrete of the girders being able to develop, without re-opening some of the cracks, a diagonal stress which was equivalent to about 6 times the stress which originally caused them. The only reasonable explanation was that the fractured surfaces of the concrete at the cracks had "knit" together and entirely healed during the interval between the tests, giving a joint which was in many instances stronger than the unbroken concrete. The tests described in the following articles on the effect of loads reapplied after failure in bond and compression were planned to throw further light on this subject. The phenomena discussed in Art. 60 and 63 are only other manifestations of the effect of retarded or interrupted hydraulicity, which have frequently been observed in tests on concrete setting under low temperatures, retempered concrete, cement reground after setting, etc.

60. *Effect of Loads Reapplied after Failure of Bond.*—Tests were made on 63 pull-out specimens to determine the effect of reapplying

* "Test of a 40-ft. Reinforced Concrete Highway Bridge," by D. A. Abrams. Proceedings of the American Society for Testing Materials, 1913.

loads to specimens which had been tested to failure some time before the retest was made. Both plain and cold-rolled round bars were used. The specimens were stored under various conditions. See Table 21. Some of these specimens have been loaded as many as five times, and the tests will be continued.

The load-slip curves for two of the groups of tests in Table 21 are given in Fig. 43 and 44. The numbers in parentheses adjacent to the curves correspond to the number given to the tests in the table and indicate the order of loading. All specimens in a group were made from the same batch of concrete.

Group (a) was a preliminary series. At the age of 5 days part of the bars were pulled out 0.001 in. at the free end and the remainder to the maximum load, which came at an end slip of about 0.01 in. Some of the specimens were then stored in water and some in air. In the subsequent tests on these specimens all bars were pulled out 0.1 in.

It makes little difference in the subsequent tests whether the bars are pulled out 0.001 in. or 0.01 in. at the first test; in fact those pulled to 0.01 in. gave somewhat higher values in the second tests. With one exception (No. 3) the specimens stored in water during the interval between the first and second tests show considerably higher values than those stored in air. For all the specimens in this group the maximum bond resistances for the third test average 24% greater than those for the second tests made 4 or 5 months earlier when the concrete was 1 or 2 months old. The fourth tests, after another interval of 4 months, when the concrete was 10 months old and the bars had previously been pulled out over 0.2 in. gave maximum bond resistances which average the same as the second test at 1 or 2 months—about 290 lb. per sq. in. It is interesting to note that the period of 1 or 2 months in air following the first tests had the effect of temporarily retarding the increase of bond resistance which was largely overcome by the subsequent period of water storage.

Group (b) consisted of two parallel series of tests on 1-in. plain round bars stored in air and in damp sand. In all these tests the bars were pulled to the maximum load, corresponding to an end slip of about 0.01 in. Two specimens for each condition of storage were tested at 5 days, 30 days, 3 months, and 1 year. At each test period, all specimens which had been tested previously were loaded to the maximum

TABLE 21.

Effect of Loads Reapplied after Failure of Bond.

Pull-out tests; embedment 8 in. in an 8-in. cylinder of concrete. Load-slip curves are given in Fig. 43 and 44. Stresses are given in pounds per square inch.

Ref. No.	No. of Tests	Age at Test	Remarks	Bond Stress at End Slip of (inches)								Max. Bond Resistance
				.0005	.001	.002	.005	.01	.02	.05	.10	
(a) 1-in. Plain Rounds; 1-2-4 Hand-mixed Concrete (1912). Bar pulled out 0.1 in. in each test unless otherwise noted.												
1	1	5 days	(1) Pulled to .001 in.	143	147	....	....	....	....	....	....	....
		40 days	(2) Stored in air	199	231	263	267	269	249	211	179	269
		6 mo.	(3) Stored in water after second test	278	310	329	340	354	306	258	215	354
		10 mo.	(4)	233	254	286	298	300	278	247	217	305
		21 mo.	(5)	223	239	243	260	265	250	229	203	265
2	2	5 days	(1) Pulled to .001 in.	169	182	....	....	....	....	....	....	....
		72 days	(2) Stored in air	179	203	229	260	268	260	232	189	268
		5 mo.	(3) Stored in water after second test	171	195	233	237	222	206	182	160	237
		10 mo.	(4)	161	183	214	227	241	220	205	171	241
		21 mo.	(5)	185	209	224	246	251	241	216	191	253
3	3	5 days	(1) Pulled to .001 in.	142	151	....	....	....	....	....	....	....
		72 days	(2) Stored in water	211	236	251	265	240	230	225	182	278
		5 mo.	(3) Stored in water	260	290	326	342	343	295	256	215	343
		10 mo.	(4) Stored in water	182	209	237	266	276	261	230	204	276
		21 mo.	(5) Stored in water	187	197	214	231	236	230	214	191	238
4	1	5 days	(1) Pulled to maximum	154	161	167	179	186	....	....	....	186
		40 days	(2) Stored in air	139	199	207	230	225	215	187	163	230
		6 mo.	(3) Stored in water after second test	171	187	207	238	240	203	183	151	240
		10 mo.	(4)	145	173	200	235	243	221	195	172	243
		21 mo.	(5)	159	175	191	211	223	217	198	179	223
5	2	5 days	(1) Pulled to maximum	189	202	214	226	232	....	....	....	232
		40 days	(2) Stored in water	243	282	289	307	301	273	235	191	307
		6 mo.	(3) Stored in water	277	328	366	398	404	384	307	273	404
		10 mo.	(4) Stored in water	230	256	292	326	336	326	298	263	340
		21 mo.	(5) Stored in water	222	234	252	272	290	285	266	233	292
6	3	5 days	(1) Pulled to maximum	180	189	199	214	218	....	....	....	218
		72 days	(2) Stored in water	266	295	313	330	327	308	262	223	330
		5 mo.	(3) Stored in water	229	275	308	326	330	302	271	235	330
		10 mo.	(4) Stored in water	215	229	246	272	285	271	257	215	285
		21 mo.	(5) Stored in water	206	212	219	242	254	250	228	207	254
(b) 1-in. Plain Rounds; 1-2-4 Machine-mixed Concrete. (1912).												
113	2	5 days	(1) Stored in air Pulled to maximum	113	124	132	149	162	....	....	....	162
		1 mo.	(2)	192	216	237	246	250	....	....	....	250
		3 mo.	(3)	177	220	243	259	....	....	....	....	269
		1 yr.	(4)	39	55	73	90	170	161	....	....	208
117	2	1 mo.	(1) do.	162	173	188	215	248	....	....	....	263
		3 mo.	(2)	165	208	234	258	265	....	....	....	288
		1 yr.	(3)	41	69	92	162	190	207	212	....	213
121	2	3 mo.	(1) do.	175	194	215	247	265	....	....	....	286
		1 yr.	(2)	38	67	113	159	178	190	198	....	198
125	2	1 yr.	(1) do.	81	119	147	173	188	217	....	....	218
115	2	5 days	(1) Stored in damp sand Pulled to maximum	134	154	165	170	177	....	....	....	177
		1 mo.	(2)	265	301	318	320	....	....	....	....	320
		3 mo.	(3)	272	310	376	384	....	....	....	....	384
		1 yr.	(4)	407	425	452	457	457	....	....	....	457
119	2	30 days	(1) do.	230	238	256	275	289	....	....	....	293
		3 mo.	(2)	307	348	376	384	....	....	....	....	384
		1 yr.	(3)	390	430	443	458	462	....	....	....	462
123	2	3 mo.	(1) do.	354	378	395	397	....	....	....	....	400
		1 yr.	(2)	407	453	478	481	....	....	....	....	485
127	2	1 yr.	(1) do.	424	443	446	450	....	....	....	....	451

TABLE 21—Continued.

(c) 1-in. Polished Rounds; 1-2-4 Machine-mixed Concrete.* (1912).

Ref. No.	No. of Tests	Age at Test	Remarks	.0005	.001	.002	.005	.01	.02	.05	.10	Max. Bond Resistance
101	2	5 days (1)	Stored in air Pulled to maximum	119	....	....	....	....	....	....	....	119
		1 mo. (2)		108	111	....	....	....	....	....	....	111
		3 mo. (3)		80	91	....	....	....	....	....	....	95
		1 yr. (4)		31	32	....	....	....	....	....	....	32
105	2	1 mo. (1)	do.	189	....	....	....	....	....	....	....	192
		3 mo. (2)		112	....	....	....	....	....	....	....	120
		1 yr. (3)		23	23	....	....	....	....	....	....	23
109	2	3 mo. (1)	do.	152	....	....	....	....	....	....	....	152
		1 yr. (2)		29	33	....	....	....	....	....	....	47
103	2	5 days (1)	Stored in damp sand Pulled to maximum	119	....	....	....	....	....	....	....	122
		1 mo. (2)		151	168	....	....	....	....	....	....	170
		3 mo. (3)		158	....	....	....	....	....	....	....	164
		1 yr. (4)		210	....	....	....	....	....	....	....	210
107	2	1 mo. (1)	do.	148	157	....	....	....	....	....	....	157
		3 mo. (2)		147	....	....	....	....	....	....	....	147
		1 yr. (3)		178	....	....	....	....	....	....	....	178
111	2	3 mo. (1)	do.	212	224	....	....	....	....	....	....	224
		1 yr. (2)		133	....	....	....	....	....	....	....	133

(d) 1-in Plain Rounds from 1912 Beam Series; 1-2-4 Hand-mixed Concrete.°
Bar pulled out 0.1 in each test.

Ref. No.	No. of Tests	Age at Test	Remarks	.0005	.001	.002	.005	.01	.02	.05	.10	Max. Bond Resistance
1054.1	3	2 mo.	(1) Stored in air	329	373	398	433	450	447	400	348	459
		7 mo.	(2) Stored in water after first test	259	298	339	373	389	370	343	394	389
		11 mo.	(3)	215	240	264	296	318	312	295	265	319
		21 mo.	(4)	251	271	288	307	323	338	314	292	338
1051.1	3	2 mo.	(1) Stored in air	300	331	361	375	382	368	334	284	386
		7 mo.	(2) Stored in water after first test	220	252	284	316	337	309	275	243	337
		11 mo.	(3)	196	220	245	275	287	287	267	231	291
		21 mo.	(4)	203	212	220	247	262	266	246	227	266
1056.1	3	2 mo.	(1) Stored in air	332	405	427	447	454	417	364	304	454
		7 mo.	(2) Stored in water after first test	198	233	265	292	306	296	274	249	306
		11 mo.	(3)	171	184	206	234	252	257	240	221	257
		21 mo.	(4)	191	199	208	229	241	248	234	219	248
1055.1	3	2 mo.	(1) Stored in air	344	397	417	441	417	379	323	262	443
		7 mo.	(2) Stored in water after first test	168	194	220	254	265	264	236	209	267
		11 mo.	(3) Stored in air after second test	188	218	233	247	251	243	229	205	248
		21 mo.	(4)	59	71	83	110	132	140	144	136	147
1059.1	3	2 mo.	(1) Stored in air	421	525	564	586	584	547	473	409	591
		7 mo.	(2) Stored in water after first test	205	252	278	315	334	339	321	296	339
		11 mo.	(3) Stored in air after second test	200	236	255	273	282	288	277	259	290
		21 mo.	(4)	69	83	96	117	134	150	183	186	187
1046.1+	3	2 mo.	(1) Stored in air	233	258	275	306	326	330	316	289	336+
		7 mo.	(2) Stored in water after first test	185	220	266	301	316	295	270	238	316+
		11 mo.	(3)	166	183	202	233	245	250	234	213	252+
		21 mo.	(4)	179	190	198	211	225	232	215	202	232+

* Groups (b) and (c) were made from the same batch of concrete. Compressive strength of 6 6-in. cubes, tested at 3 mo., 2720 lb. per sq. in.

° Compressive strength of 18 6-in. cubes, tested at 63 days, 2360 lb. per sq. in.

+ 1-in. plain square bars.

again. Thus, as indicated in the table, some of the specimens have been loaded to their maximum as many as four times. The load-slip curves are given in Fig. 43. The notable feature of these tests is that the water-stored specimens which had been previously loaded to a maximum once, twice, or three times, gave values greater than or equal to those found in the specimens, which at the same age, were loaded for the first time. The same statement is true of the air-stored specimen, except that all the 1-year tests, both on specimens which had been previously loaded and those loaded for the first time, gave lower values. The two pairs of specimens tested at 5 days gave nearly identical results, as may have

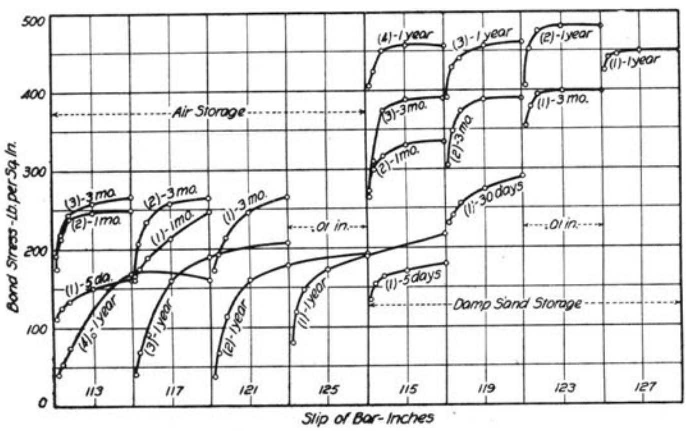


FIG. 43. LOAD-SLIP CURVES FOR LOADS REAPPLIED AFTER FAILURE OF BOND.

been expected, since the difference in storage conditions would not affect the relative strengths at that age. During the interval between the first and second tests of these specimens (5th to 30th day) the relative increase in maximum bond resistance is about the same for air storage and damp sand storage—37% and 30%; during the interval between the first and second tests of specimens No. 117 and 119 (1st to 3rd month) the increase was 9% and 31%, respectively.

Group (c) was similar in every way to group (b) except that polished bars were used. It was thought that by comparing the behavior of plain and polished bars in these tests, additional information as to the components of bond resistance would be obtained. Generally, only one observation on slip of the end of the polished bar within the maximum load could be obtained. The maximum bond resistance came in

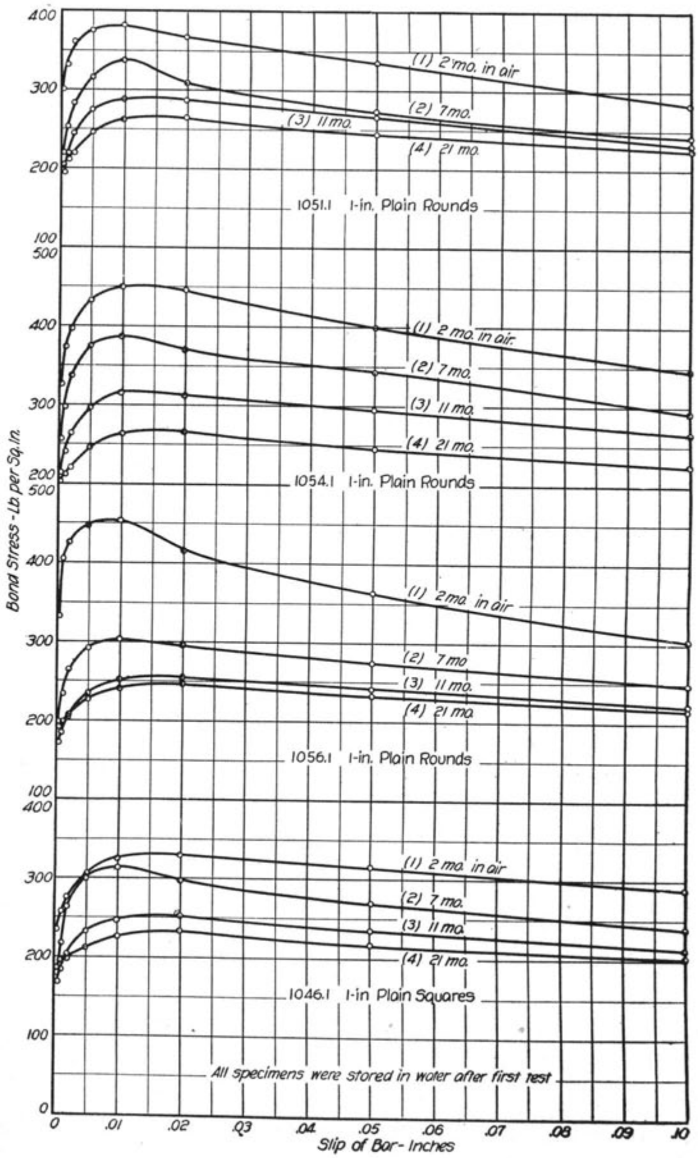


FIG. 44. LOAD-SLIP CURVES FOR LOADS REAPPLIED AFTER FAILURE OF BOND.

all the tests at a slip of about 0.001 in. The results of these tests are not as consistent as those on plain bars, but some interesting facts are brought out.

A study of the tests in groups (b) and (c) indicates that the bond resistance which is developed before the free end of the bar of the size used in these tests has slipped, say, 0.001 in. is due to adhesion. The value of this adhesion is dependent on the amount of moisture present and the age of the concrete. In the case of the polishd bars the original bond resistance was generally regained in the specimens stored in damp sand, but the increase with age was small. The air-stored specimens show about the same bond resistance as the sand-stored specimens in the first tests, but upon reapplication of load there is a material falling-off in strength. With the round bars of ordinary surface the adhesive resistance was entirely restored, except in the 1-year tests on air-stored specimens. The amount of increase in bond resistance apparently depends upon the presence of the water necessary for the continuation of the hydraulic action of the cement. The drying-out of a specimen after a certain period interferes with the phenomenon here discussed.

Group (d) included 6 sets of pull-out specimens from the 1912 beam series. All of these specimens were stored in air up to the time of the first test at the age of 2 months. In each of the tests the bar was pulled to an end slip of 0.1 in. The load-slip curves are given in Fig. 44. These tests are of interest in showing what may be expected when the specimens have attained a considerable age before the first failure of bond. In no instance were the values from the second to the fourth tests as high as found in the first tests. The average values for all the specimens with plain round bars (disregarding minor variations in storage conditions) are 406, 246, 220 and 167 lb. per sq. in. for the first, second, third and fourth tests, respectively, at a slip of 0.001 in.; and 467, 327, 281 and 237 lb. per sq. in. for maximum bond resistance. It will be recognized that the conditions in this group were the most adverse of any of the groups in which the load was reapplied after failure. The bond resistance did not subsequently reach the amount found in the first tests, but it is noteworthy that even at the fourth loading comparatively high values of bond resistance were found.

The foregoing tests are of value in showing that a considerable displacement of the bar, and a frequent disturbance of the bond between the concrete and steel, even several days or weeks after placing the concrete, does not necessarily produce permanent weakness. If disturbance occurs after a longer period the final effect will probably depend upon whether sufficient moisture is present in the concrete. These results give added confidence to the permanency of bond and indicate that plain bars may properly be used in certain classes of work in which they have sometimes been considered unsuitable. It should be noted that the specimens were unstressed in the interval between loadings.

61. *Bond Resistance of Concrete which Set under Pressure.*—As a means of gaining further knowledge as to the nature of bond resistance, a few tests were made on specimens in which the concrete was caused to set under pressure. 1-in. plain rounds, 1-in. cold-rolled rounds and 1⅛-in. corrugated rounds were used. The pressures used were 0, 6, and 100 lb. per sq. in. The specimens were molded in the usual way, except that in the specimens which set under a pressure of 100 lb. per sq. in. the long end of the bar was upward. The pressure was applied immediately after placing the concrete in the form. A circular plate with a central hole which allowed the rod to pass through was placed inside the form on the fresh concrete. The 6-lb. per sq. in. pressure was obtained by piling weights on the cover plate; the 100-lb. per sq. in. pressure was obtained by setting the form in a pan on the bed of a testing machine and running the head down onto a nest of springs, which transmitted the load to the cover plate. These loads remained on the specimens for 5 days. After removal from the forms, the specimens were stored in damp sand. The tests are summarized in Table 22. The load-slip curves are given in Fig. 45. The increase of maximum bond resistance and other properties with the pressure under which the concrete set are shown in Fig. 47. The maximum bond resistance for plain bars in concrete which set under pressures of 6 and 100 lb. per sq. in. are 9% and 91% higher, respectively, than the corresponding values for concrete setting under no pressure. In the case of the cold-rolled rounds, the increase due to the pressure was slight. The value for 6 lb. per sq. in. pressure seems abnormally high.

The corrugated bars show a large increase in bond resistance due to the pressure. These values cannot be compared directly, since some of the specimens were tested without removing the steel-pipe forms in which they were made. However, the corrugated bars show an increase in bond resistance of about 100% as compared with specimens tested under similar conditions which had set without pressure. The specimens which set under a pressure of 6 lb. per sq. in. (No. 91) show an increase of 66% to 90% as compared with the values for the same amount of slip in the specimens setting without pressure. The concrete blocks split in these two sets of tests at the same slip—0.02 in. Specimens No. 93 made and tested in a steel form gave very high values. No. 89 shows the effect of leaving the steel form in place during the test of a specimen which set without pressure; No. 95 shows the effect of casting the specimen with the long end of the bar upward. For a discussion of other tests with corrugated bars showing the effect of reinforcing the block against bursting, see Art. 64.

TABLE 22.

Bond Resistance of Concrete which Set under Pressure.

1-2-4 concrete, machine-mixed; embedment 8 in. Age at test 80 days.
Stresses are given in pounds per square inch.

Ref. No.	Number of Tests	Characteristics	Bond Stress at End Slip of—inches								Maximum Bond Resistance
			.0005	.001	.002	.005	.01	.02	.05	.10	
		(a) 1-in. Plain Rounds.									
71	2	Without pressure............	273	302	328	345	351	350	320	290	353
73	6	Concrete set 5 days under pressure of 6 lb. per sq. in.......	221	256	288	332	363	378	351	297	378
77*	2	Concrete set 5 days under pressure of 100 lb. per sq. in.....	387	457	546	634	671	673	570	477	674
		(b) 1-in. Cold-Rolled Rounds.									
79	2	Without pressure...........	141	......	......	......	......	......	......	......	141
81	1	Concrete set 5 days under pressure of 6 lb. per sq. in.......	222	......	......	......	......	......	......	......	222
83	2	Concrete set 5 days under pressure of 100 lb. per sq. in.....	149	......	......	......	......	......	94	81	163
		(c) 1⅛-in. Corrugated Rounds.									
85	2	Without pressure. No spiral..	234	248	258	278	312	341	......	......	375
87	2	Without pressure. Spiral—See Fig. 1 (b)............	244	279	314	359	412	517	809	1115	1115
89	2	Without pressure, in steel pipe form......................	347	404	420	438	516	605	855	1070	1070
91*	2	Concrete set 5 days under pressure of 6 lb. per sq. in.......	380	413	458	503	617	672	......	......	720
93*	2	Concrete set 5 days under pressure of 100 lb. per sq. in.....	682	937	1180	1417	1600	1733	......	......	1960
95	4	Cast with long end of bar upward as in Fig. 1 (c); spiral..	408	508	590	687	793	881	1140	1250	1250

* Specimens molded in forms made of 8-in. sections of 8-in. steel pipe. The forms were cut off at age of 5 days.

° Tested with steel pipe form in place.

62. *Compression Tests of Concrete which Set under Pressure.*—In order to make a further study of the effect of allowing concrete to set under pressure, a series of compression tests was made on 8 by 16-in. cylinders. It is believed that these tests are of sufficient interest to warrant their inclusion in this report. Seventeen cylinders were

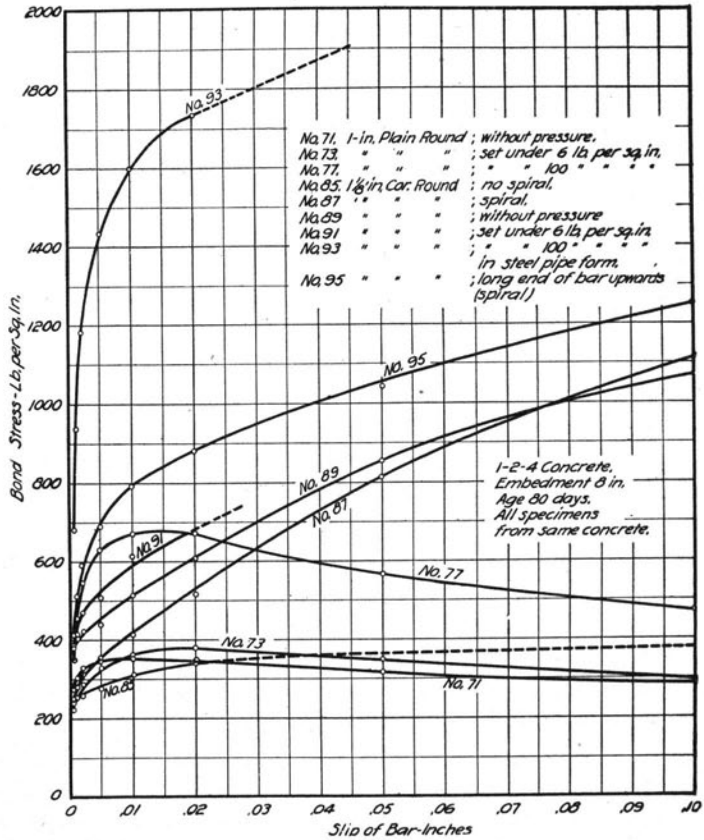


FIG. 45. LOAD-SLIP CURVES FOR MISCELLANEOUS PULL-OUT SPECIMENS.

made from a single batch of concrete. Two of these were allowed to set under normal conditions; three set under a pressure of 6 lb. per sq. in.; five set under 20 lb. per sq. in. and five under 100 lb. per sq. in. Some of the specimens remained under pressure for 1 day, some for 7 days and some during the entire period of storage. Two specimens set for seven days under 3 lb. per sq. in., after which they were placed in a testing machine and loaded at the rate of 100 lb. per sq. in. per week until a total load of 500 lb. per sq. in. had been applied; this load then remained on the cylinders until they were tested at the age of 80 days. The method of applying the pressure during the setting and hardening of the concrete was similar to that described in Art. 61 for the pull-out specimens.

Details of these tests are given in Table 23. Five of the cylinders were tested at 7 days; and the remainder at age of 80 days. The retest of the five cylinders which were originally tested to failure at 7 days will be discussed in Art. 63.

Deformations were measured over a 10-in. gage length by means of a wire-wound instrument which was a modified form of the Johnson extensometer. The weight of the concrete, the compressive strength, and the initial modulus of elasticity of the cylinders are given in the table. Typical stress-deformation curves are given in Fig. 46. The variation in compressive strength, initial modulus of elasticity, and density with the change in pressure are shown in Fig. 47.

The first notable feature of these tests is that it makes little or no difference in the strength and properties of the cylinders, whether the concrete remained under pressure for 1, 7 or 77 days. In other words, if the concrete takes its final set and hardening begins under pressure there is nothing to be gained by continuing the pressure for a longer period. For this reason the values for all the cylinders for each pressure which were tested for the first time at an age of 80 days were averaged in computing the percentages in Fig. 47. The consistency of the values indicates that the pressure probably had the effect of producing an unusually homogeneous concrete and justifies us in placing confidence in the results of the tests. The stress-deformation curves in the lower right section of Fig. 46 show the effect of different pressures on the compressive strength and the modulus of elasticity of these cylinders. The compressive strength was increased from 1840 lb. per sq. in. for no pressure to 3140 lb. per sq. in. for a pressure of 100 lb. per sq. in.—an increase of 73%. The compressive strength of the 8-in. cylinders setting without pressure is 91% of that for 6-in. cubes tested at the same age. The curve in Fig. 47 indicates that over one-half the increase occurred at pressures below 20 lb. per sq. in. It seems probable that the strength of the concrete which was subjected to a pressure of 100 lb. per sq. in. was considerably reduced by the loss of the water which was forced out when the pressure was first applied, owing to openings around the cover plate. On account of the danger of getting the

TABLE 23.

Compression Tests of Concrete which Set under Pressure.

The test pieces were cylinders 8 in. in diameter, 16 in. long. Concrete 1-2-4, machine-mixed. All specimens were made from the same batch. The cylinders were stored in damp sand after seven days except those setting under pressure for a longer period and those tested originally at age of seven days. The cylinders which set under pressure longer than seven days remained in the forms until they were prepared for testing; those tested at seven days were placed in water until the time of the second test.

The compressive strength of 6 6-in. cubes tested at 77 days was 2010 lb. per sq. in.

Ref. No.	Age at Test days	Pressure During Setting lb. per sq. in.	Duration of Pressure days	Weight of Concrete lb. per cu. ft.	Compressive Strength lb. per sq. in.	Initial Modulus of Elasticity lb. per sq. in.
501	7	0	0	142.5	725	1 500 000
501	80	0	0	.....	1850*	2 370 000*
502	80	0	0	.....	1820	3 100 000
503	80	6	1	.....	2220	3 480 000
504	80	6	7	.....	2170	3 600 000
505	80	6	77	142.5	2220	3 820 000
506	7	20	1	148.5	1240	2 000 000
506	80	20	1	.....	2450*	3 800 000*
507	80	20	1	.....	2350	3 880 000
508	7	20	7	148.0	1087	2 250 000
508	80	20	7	.....	1935*	3 240 000*
509	80	20	7	.....	2670	3 800 000
510	80	20	77	148.0	2850	3 520 000
511	7	100	1	148.2	1570	2 500 000
511	80	100	1	.....	3060*	4 400 000*
512	80	100	1	147.0	3110	4 400 000
513	7	100	7	149.5	1450	2 500 000
513	80	100	7	.....	2430*	3 800 000*
514	80	100	7	149.0	3140	4 000 000
515	80	100	77	148.0	3160	4 400 000
516°	80	...	..	143.0	1865	2 640 000
517°	80	...	..	145.0	2000	2 720 000

* Second test on the same specimen.

° Set under pressure of 3 lb. per sq. in. for seven days; forms removed and cylinders placed in testing machine, under pressure as follows:

100 lb. per sq. in. 7th to 14th day;
200 lb. per sq. in. 14th to 21st day;
300 lb. per sq. in. 21st to 28th day;
400 lb. per sq. in. 28th to 35th day;
500 lb. per sq. in. 35th to 80th day.

The storage of these cylinders differed from the others in that they were exposed to the air after age of seven days.

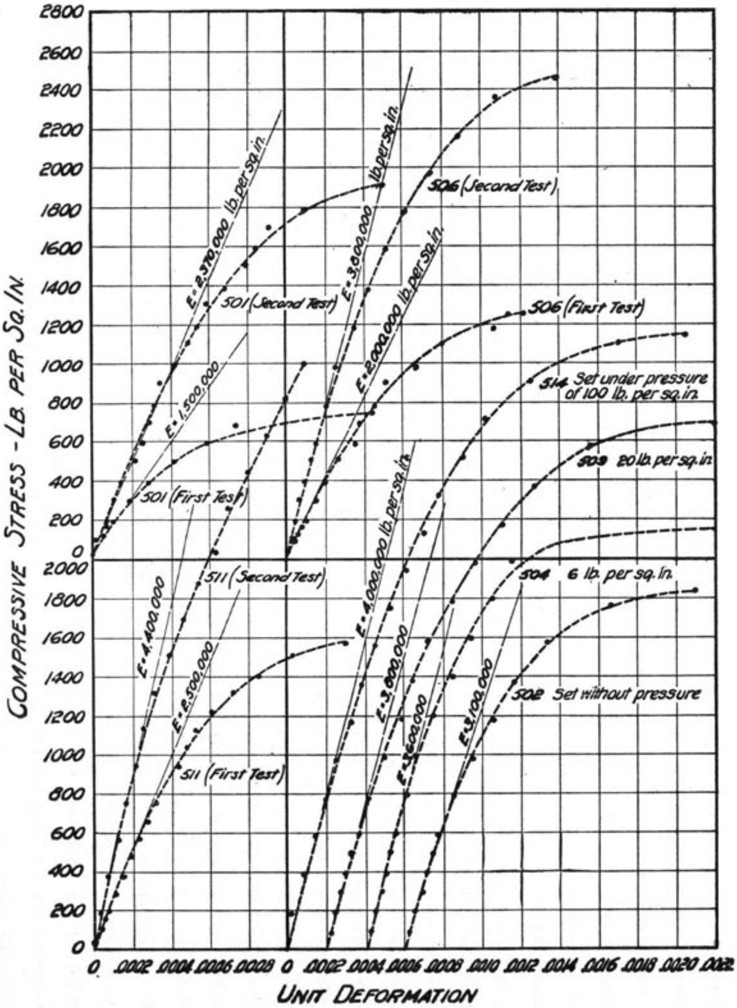


FIG. 46. STRESS-DEFORMATION CURVES FOR 8 BY 16-IN. CONCRETE CYLINDERS.

cover plate wedged in the form in applying the pressure to the fresh concrete, a close fit was impracticable. Under a pressure of 100 lb. per sq. in. the length of the 16-in. cylinder was shortened nearly 1 in. and as much as a quart of water was forced out.

The initial modulus of elasticity increased from 3 100 000 lb. per sq. in. for the cylinders without pressure to 4 300 000 lb. per sq. in. for those setting under 100 lb. per sq. in.; an increase of about 37%. As in the case of the compressive strength, over one-half of this increase occurred below a pressure of 20 lb. per sq. in. The cylinders which set for 7 days under a pressure of 3 lb. per sq. in. and were gradually loaded to 500 lb. per sq. in. (No. 516 and 517) gave about the same values as those setting without pressure. Apparently the difference in storage conditions nearly counteracted the effect due to pressure. The increase in compressive strength and modulus of elasticity with the pressure under which the concrete sets is more pronounced in the 7-day than in the 80-day tests.

The density of the concrete as determined by the weight of the cylinders was increased about 4% by the pressure of 100 lb. per sq. in.

63. *Effect of Loads Reapplied after Failure in Compression.*—An interesting instance of "autogenous healing" in concrete was found in the retest of five cylinders at the age of 80 days which had been loaded to their ultimate strength in compression at 7 days. One of the cylinders had set under no pressure; two set under 20 lb. per sq. in. and two under 100 lb. per sq. in. During the period from the 7th to the 80th day the cylinders were stored in water. The results of the first and second tests have been bracketed together in Table 23. Load-deformation curves for three of the cylinders are given in Fig. 46. In all the 7-day tests loading was continued until there was a distinct drop in the beam of the testing machine and the extensometer showed a rapid increase in deformation. The fact that the load-deformation curves are nearly horizontal and that a unit-deformation greater than 0.0012 in. was produced in all these cylinders show that they received their ultimate loads in the 7-day tests. Numerous vertical cracks and surface flaking could be seen on most of the cylinders. The compressive strength and modulus of elasticity for the 80-day tests averaged 93% and 64%, respectively, greater than for the 7-day tests of the same cylinders. The average compressive strength and modulus of elasticity for the retested cylinders are 91% and 92%, respectively, of the values for similar cylinders which were tested for the first time at 80 days. It is note-

worthy that the cylinders which set under pressure behaved in much the same way as those setting under normal conditions.

Apparently a compressive stress equal to the ultimate resistance of concrete applied as much as 7 days after mixing (as long as the specimen is not entirely shattered) does not necessarily permanently destroy its usefulness, if this failure is followed by a period of rest in the presence of sufficient water to permit hydraulicity to continue.

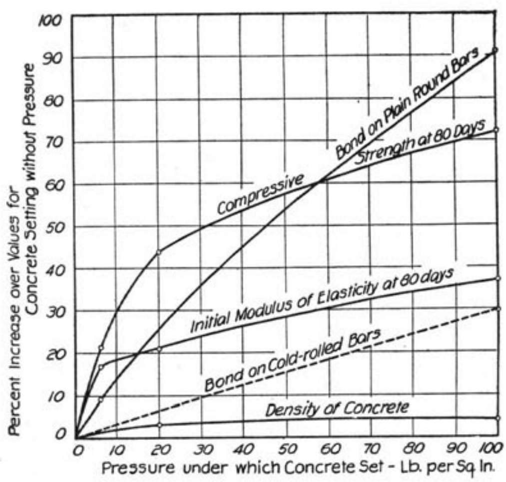


FIG. 47. EFFECT OF PRESSURE DURING SETTING ON THE PROPERTIES OF CONCRETE.

64. *Effect of Reinforcing the Pull-out Specimen against Bursting.*—In many of the pull-out tests with deformed bars, the concrete blocks were reinforced against bursting by means of 6 or 7 turns of a ¼-in. wire spiral placed inside the forms. It was desired to determine what effect this restraint had on the load-slip relation and on the maximum bond stresses developed. Several specimens made with corrugated square and corrugated round bars were reinforced as indicated above and others from the same batch were without reinforcement. The results of these tests are given in Table 24. In nearly every case the specimens reinforced with the wire spiral gave higher bond stresses at all stages of the test than those without reinforcement. The difference is not very great for ages of 2 to 7 days. For the tests made at 28 days or over the bond resistance at a slip of 0.001 in. for the specimens with the spiral averaged about 15% higher than those not reinforced; at the maximum load the values are about 50% higher.

TABLE 24.

Effect of Reinforcing the Concrete Block against Splitting.

Pull-out tests, embedment 8 in. All specimens were stored in damp sand.
Stresses are given in pounds per square inch.

Ref. No.	Age at Test days	Number of Tests	Remarks	Bond Stress at End Slip of—Inches							
				.0005	.001	.002	.005	.01	.02	.05	.01
(a) ¾-in. Corrugated Squares, 1-1-2 Hand-mixed Concrete (Batch 20).											
1	2	2	Spiral........................	86	96	102	121	136	159	207	250
2	2	2	Without spiral................	97	111	117	131	154	174	220	236
3	4	2	Spiral........................	145	157	174	208	234	268	315	351
4	4	2	Without spiral................	108	129	148	177	196	230	258	259
5	7	2	Spiral........................	167	177	198	228	273	317	396	447
6	7	2	Without spiral................	154	166	174	218	253	298	322	322
7	28	2	Spiral........................	309	329	343	377	422	507	683	827
8	28	2	Without spiral................	258	286	316	393	480	527	......	527
9	60	5	Spiral........................	445	498	555	655	793	965	1101	1145
10	60	4	Without spiral................	338	399	419	499	......	......	......	771
11	15 mo.	2	Spiral........................	709	892	1015	1165	1340	1480	......	1525
12	15 mo.	2	Without spiral................	645	778	888	......	......	......	......	1025
(b) ¾-in. Corrugated Squares, 1-1-2 Hand-mixed Concrete (Batch 23).											
13	2	1	Spiral........................	86	92	102	138	166	200	270	312
14	2	1	In 8-in. steel pipe form §......	91	114	119	140	166	195	271	326
15	2	2	Without spiral................	93	105	112	129	142	180	211	214
17	4	1	Spiral........................	146	158	182	233	279	325	408	444
18	4	1	In steel pipe §................	131	145	169	206	249	300	405	463
19	4	2	Without spiral................	101	118	123	151	178	213	258	264
20	7	1	Spiral........................	192	216	246	310	375	450	533	555
21	7	1	In steel pipe §................	148	171	190	243	300	376	495	562
22	7	2	Without spiral................	150	159	177	194	210	214	242	274
23	39	1	Spiral........................	390	433	458	562	657	796	894	906
24	39	1	In steel pipe §................	351	378	434	554	695	861	1075	1152
25	39	2	Without spiral................	386	413	453	527	579	......	......	700
26	61	2	Spiral........................	577	660	749	887	1019	1104	1134	1152
27	61	2	Without spiral................	378	439	489	607	717	......	......	819
28	5 mo.	2	Spiral........................	516	586	657	829	1023	1195	......	1329
29	5 mo.	2	Without spiral................	474	564	639	770	894	1024	......	1070
(c) 1⅛-in. Corrugated Round, 1-2-4 Hand-mixed Concrete.											
30	76	5	Spiral........................	281	306	328	374	438	535	677	846
31	76	1	Without spiral................	235	260	270	286	307	328	392	457
(d) 1⅛-in. Corrugated Round, 1-2-4 Machine-mixed Concrete (1912).											
32	80	2	Spiral........................	244	279	314	359	412	517	809	1115
33	80	2	In 8-in. steel pipe §...........	347	404	420	438	516	605	855	1070
34	80	2	Without spiral................	234	248	258	278	312	341	......	375

§ Blocks were molded in an 8-in. length of 8-in. steel water pipe which remained in place during the test.

In order to study the effect of a greater amount of restraint against bursting, part of the specimens were molded and tested in forms consisting of 8-in. lengths of 8-in. steel water pipe. The specimens with solid pipe forms gave values about the same as those with the spiral, during the earlier stages of the tests, but as may have been expected, they gave much higher values of maximum bond resistance. These tests indicate that the restraint of the spiral reinforcement is effective in raising the bond resistance in pull-out tests with deformed bars.

Fig. 45 gives load-slip curves for a few tests which show the effect of reinforcing the concrete block against bursting, the effect of causing the concrete to set under pressure and the effect on the corrugated bar tests of molding the specimen with the long end of the bar upward.

B. Reinforced Concrete Beam Tests.

65. *Preliminary.*—It is in the design of reinforced concrete beams that a correct knowledge of the bond resistance between the concrete and the steel is most important. The study of reinforced concrete beams with special reference to bond stresses was begun at the University of Illinois in 1909; additional series of beam tests designed for the study of bond stresses were made in 1911 and 1912. The results of 110 beam tests are given in this bulletin. The dimensions of the beams were: width 8 in., depth 12 in. (10 inches to the center of the steel) and span length 5 to 10 ft. Typical forms of reinforced concrete beams are shown in Fig. 2. The longitudinal reinforcement usually consisted of a single straight bar of large diameter placed in the middle of the width of the beam. These bars extended to the ends of the beams. Vertical stirrups were frequently used as web reinforcement. With a few exceptions which are noted in the tables, the beams were loaded at the one-third points of the span. The usual span length was 6 in. less than the total length of the beam; in some of the 1911 tests beams 7½ and 8½ ft. long were loaded on a span of 6 ft. with the ends overhanging the supports 9 in. or 15 in., instead of 3 in. as in the other beam tests. Bars of large diameter and beams of comparatively short span lengths were used in order to develop high bond stresses in comparison with the other stresses in the beam, and thus to produce bond failures.

66. *Measurements of Slip of Bar.*—In the beam tests the slip of the ends of the reinforcing bar was measured by means of Ames gages as in the pull-out tests. The instrument was carried by a wooden or

metal yoke which was attached to the ends of the beam in such a position that the movable head-piece of the instrument had a direct bearing against the end of the bar. As the test progressed, the amount of slip at each end of the bar was noted. In many of the beams of the series of 1911 and 1912 the slip of bar was measured at numerous points along the length. Openings about 1 in. in diameter were cut or formed in the concrete under the reinforcing bar at points where measurements of slip were desired. Plugs of 3/8-in. square steel were screwed firmly into threaded holes in the bar. The gage was carried by a metal bracket attached to a steel plate which was fastened to the concrete by plaster of paris in two places on either side of the plug. The plunger of the gage rested against the steel plug so that a movement of the reinforcing bar in either direction with respect to the concrete would be indicated by the pointer. As many as 13 such instruments were used in some of the tests. The positions of these instruments are shown for typical tests in Fig. 56.

The amount of slip which has been termed "first slip of bar" in the tables corresponds to a movement of about 0.0002 in. We are justified in using a smaller quantity as a measure of first end slip in beams than was used in the pull-out tests, for the following reasons: (1) Measurements from the yoke to points on the concrete of the end of the beam near the bar do not show appreciable deformation in the concrete at any stage of the test. This is probably due to the unstressed condition of the concrete at the end of a beam. (2) The load-slip curves for the beam tests show that as soon as the slip at the end of the bar reaches about 0.0002 in., it rapidly increases with a further application of load. (3) Tests made on beams by allowing the load which produced a very small amount of slip at the end of the bar to remain constant for several hours or days indicate that the ultimate bond resistance probably would be developed under the indefinitely continued application of loads which produce at first an end slip as small at 0.0002 in. The tests in which slip of bar was measured at intermediate points are discussed in detail in Art. 94.

67. *Computation of Stresses in a Reinforced Concrete Beam.*—An analysis of the stresses in a reinforced concrete beam was given in Bulletin No. 4 of the University of Illinois Engineering Experiment Station, "Tests of Reinforced Concrete Beams," by A. N. Talbot, and reference may be made to that bulletin for methods of computing the stresses given in the following tables. In that analysis it was shown

that for the assumptions of beam theory the bond between concrete and steel in a reinforced concrete beam is a function of the vertical shear. The bond unit-stress was expressed by

$$u = \frac{v}{m\,o\,d'}$$

Where v = the total vertical shear,
m = the number of bars,
o = the perimeter of one bar,
d' = the effective depth of the beam, or the distance between the center of the steel and the centroid of the compressive stresses.

The formula assumes that the reinforcing bar ends at the point of support. As in the test beams the bar extended beyond the point of support 3 in. or more, the amount of available bond surface will be greater than that assumed in the analysis, but generally in the calculations this additional bond surface will be disregarded and the formula used as given above without modification.

It is recognized that this analysis does not consider all the phenomena of bond action. It will be seen below that after slip of bar becomes appreciable, the bond stress in a beam is not distributed as indicated by the formula. However, instead of attempting to take into account the effect of slip of bar and the cracking of the concrete, the values computed by the above formula will be used. These nominal values of bond resistance form a useful basis of comparison in a series of tests in which the dimensions and make-up of the beams are similar.

68. *Phenomena of Beam Tests.*—If a bar which is embedded in a prism of concrete is subjected to a pull at its ends a part of the tensile force is transmitted to the concrete and a bond stress is developed between the steel and the concrete which may be said to be due to the stiffness of the concrete or its resistance to stretch. When the concrete has been distended to its limit of stretch or to its limit of tensile strength, a break occurs and the concrete adjoining the break springs back toward the unbroken concrete, there is a slipping along the bar, and a minute crack forms at the break. The size of the crack and the amount of the slip will depend upon the relative dimensions of concrete and steel. It is evident that some tensile stress will remain in the unbroken concrete and some bond stress between concrete and steel even after slip has occurred, and that with increased tension in the bar there will be further

stretch in the concrete or further slip of the bar or more cracks in the concrete. For want of a better one, the term "anti-stretch slip" may be used for this slip of bar which is due to the stiffness or springiness of the concrete after cracking. At what strain this anti-stretch slip occurs and how far apart the cracks will be may be expected to be a function of the size and periphery of bar and the condition of its surface and the quality of the concrete and the section of concrete which is tributary to the reinforcing bar.

It is well here to call attention to the fact that a tension break in the concrete may occur without its presence being visible to the eye. The stretched concrete to the side of the break will act as a spring and tend to pull the concrete back from the break. If this elastic force is greater than the bond resistance slip will occur and the crack will widen and become perceptible. Such cracks are very fine. The whitewashing of the surface of the beams materially assisted in detecting these cracks at an early stage of their development, and doubtless many of them would not have been seen on the natural surface of the concrete. It may be added that the term "anti-stretch slip" has been used sometimes in the bulletin to cover the elastic force which goes with the slip.

In the case of a beam which is loaded symmetrically at the one-third points, the region between the two loads carries no vertical shear and there is no bond stress due to normal beam action as it is usually analyzed. However, this is the region of greatest longitudinal stress and hence the region in which a phenomenon similar to that just described will exist to a considerable degree. At the beginning of loading, the concrete itself will carry the greater part of the tensile stress and a part will be transmitted to the reinforcing bar. In the later stages, after cracks have formed, it may be simpler to consider the tension to be carried primarily by the bar and the concrete to form the web and the enveloping medium. At the formation of tension cracks, the phenomenon of anti-stretch slip described in the preceding paragraph will exist. The reinforced concrete beam tests to be described indicate that a slip of bar took place in this region at loads below those at which minute cracks on the whitewashed face of the beam appeared, and considerably below the loads at which they have been noted in beams having only the usual concrete surface for inspection. In general, this early interior slip of bar was noted at a tensile stress in the bar of about 6000 lb. per sq. in. The distance apart of these cracks and their relation to the form and size of bar will be discussed with the details of the tests.

For the region outside the load points, that is, in the outer thirds of the span length, for the method of loading generally used, shearing and other web stresses exist, and due to the beam action bond stresses between the concrete and steel are developed which may be termed beam bond stresses. By the usual analysis, for the loading used, these bond stresses are nominally uniform from load point to support. The anti-stretch slip may be expected to exist here also, especially in the part near the load points, and the existence of this slip and bond stress concurrently with the beam bond stress makes a considerable complication and may be expected greatly to modify the distribution of the bond stresses over the length of the bar, and to affect resistance to beam bond stresses.

In the tests of beams loaded at the one-third points, the beam exhibits considerable stiffness up to the load which causes the first tension cracks in the concrete. After this point, the beam deflection increases more rapidly and continues at a nearly constant rate until failure is imminent. A marked change in the rate of deflection follows the diminution in effective tensile resistance of the concrete and is coincident with the stage when anti-stretch slip first develops prominently in the middle third of the beam. Due to the inequalities in the tensile resistance of the concrete and to the development of anti-stretch slip the tension cracks form at certain points instead of being closely spaced, and a large part of the increase in length of the lower fibers is concentrated at these cracks. An examination of the photographs and sketches of the beams after failure will show that tension cracks form through the region of the middle third and generally a short distance outside with usually other tension cracks farther out.

For the stage of the test at which cracks first appeared at the load points or a short distance outside, the bar showed a measurable slip just beyond the crack (nearer the end). It was necessary to increase the load 50% to 300% before slip was produced at the end of the bar; the amount of increase varied principally with the distance between the load point and the support. We may expect then that a bond stress nearly as great as the ultimate bond resistance was being developed for a short distance beyond the crack, much of which was due to the condition which produces anti-stretch slip of bar. At this stage of the test the bond stress at the supports was only a small part of the maximum bond resistance. The tests indicate that when the maximum bond stress was first developed outside the load points the bond stress at the support was not more than, say, 15% to 40% of the maximum bond resistance. As the bar was further stressed by an additional load applied to the beam, the bond stress near the crack decreased on account of excessive slip of bar and the region of full bond resistance was thrown more and more toward the support. Later in the test, due to the combination of beam bond stress and anti-stretch slip, another crack was formed a few inches nearer the support. The opening of a second crack had the effect of reducing the bond stress between the cracks and the tensile stress in the bar was increased toward the support. As the loading progressed this process continued with the piecemeal development of the maximum bond resistance and the subsequent reduction of bond due to excessive slip over the portion of the bar affected, until the effective embedded length of the bar was no longer able to withstand the bond stresses developed and failure from slip of bar soon followed. It is clear that the unbroken embedded length of bar at the ends of the beam which takes the principal portion of the total bond stress during the last stages of the test, will depend upon the relative dimensions of the bars and the beam and upon the bond, tensile and shearing resistance of the concrete. The beam tests discussed below show how this distance varied for a variety of conditions.

Fig. 57 to 63 show the appearance of representative beams after testing. The surfaces of the beams had been whitewashed before the tests in order to facilitate the tracing of cracks. The positions of the load-points and supports are shown by vertical arrows. The surface cracks, which were generally very fine, were traced with black paint on the surface of the beams in order that the location of the cracks may be shown on the photographs. The numbers near the cracks indicate the extension of the cracks as the test progressed expressed in thousands of pounds load. In the beams in which slip of bar was measured at intermediate points, the positions of the instruments are indicated by the numbers inside circles; the points at which tensile deformations in the longitudinal bar were measured in the tests of certain beams are indicated in the same way.

The load-slip curves for representative beams in each group are given in Fig. 69 to 76, inclusive; load-deflection and end-slip-of-bar curves are given in Fig. 77 to 86, inclusive. These diagrams give important indications as to the effect of the different variables in the make-up or loading of the beams.

a. 1909 Beam Tests.

69. *Outline of Series.*—In 1909 eleven reinforced concrete beams were tested with special reference to a study of bond stresses. Data of the beams and tests are given in Tables 25 and 26. These beams were considered as a preliminary series; no companion pull-out specimens were made.

TABLE 25.

DATA OF REINFORCED CONCRETE BEAMS—1909 SERIES.

1-2-4 hand-mixed concrete; Chicago AA portland cement.
Each beam was reinforced with a single longitudinal bar.
All beams were 8 in. wide; total depth 12 in.; depth to center of steel 10 in.; length 6½ ft.

Beam No.	Longitudinal Reinforcement		Stirrups (Round bars 4 in. apart)	Mixture by Weight	Beam from Same Batch	Compression Tests of 6-in. Cubes	
	Kind of Bar	Per cent				Age at Test days	Average of 3 Tests lb. per sq. in.
120	1-in. plain round	0.98	⅝ in.	1-2.35-4.15	121	82	1420
121	1-in. plain round	0.98	⅝ in.	1-2.35-4.15	120	82	1420
201	1-in. plain round	0.98	⅝ in.	1-2.53-4.40	202	62	1757
84	1¼-in. plain round	1.53	⅝ in.	1-2.34-4.27	85	65	1722
203	1¼-in. plain round	1.53	½ in.	1-2.52-4.47	204	63	1573
204	1¼-in. plain round	1.53	½ in.	1-2.52-4.47	203	63	1573
117	1-in. cup	1.25	⅝ in.	1-2.23-3.93	118	87	1960
62	1⅛-in. corrugated round	1.25	⅝ in.	1-2.44-4.23	...	65	1762
202	1⅛-in. corrugated round	1.25	⅝ in.	1-2.53-4.40	201	62	1757
85	¾-in. corrugated square	0.70	⅝ in.	1-2.34-4.27	84	65	1722
118	1-in. twisted square	1.25	⅝ in.	1-2.23-3.93	117	87	1960

The average compressive strength of 6 sets of 6-in. cubes was 1700 lb. per sq. in.

All the beams were identical as to materials and external dimensions. 1-2-4 hand-mixed concrete made with Chicago AA cement was used. Each beam was reinforced with a single bar which extended flush with the ends of the beam. The size and spacing of vertical stirrups is given in Table 25. The age at test averaged about 100 days. All beams were loaded at the one-third points of a 6-ft. span. In all but one test (Beam No. 84) the load was applied progressively to failure. In the test of Beam No. 84, load was applied until one end of the bar showed an appreciable slip; the load was then released and reapplied. This test is discussed in detail in Art. 90.

70. *Bond with Plain Round Bars.*—End slip began in the beams reinforced with a 1-in. round bar at an average bond stress of 192 lb. per sq. in.; and for the 1¼-in. round at 211 lb. per sq. in. The average maximum bond resistance was 279 lb. per sq. in. for the 1-in. bars and 303 lb. per sq. in. for the 1¼-in. bars. The load-deflection and load-slip curves for Beams 121 and 204 are given in Fig. 77.

TABLE 26.

Tests of Reinforced Concrete Beams—1909 Series.

All beams were loaded at the one-third points of a 6-ft. span; overhang 3 in. at each end.

Loads are given in pounds; stresses in pounds per square inch.
In computing unit stresses, the weight of the beam was considered.

Beam No.	Age at Test days	Load at First Outer Crack	At First Slip of End of Bar°		At Maximum Load				Failure of Beam
			Applied Load	Computed Bond Stress	Applied Load	Tensile Stress in Steel	Vertical Shearing Stress	Computed Bond Stress	
120	112	11 000	10 000	198	11 700	22 100	89	230	Slow bond failure at S. end
121	112	10 000	10 000	198	14 500	27 100	111	281	Bond at S. end.
201	88	10 000	10 000	180	16 900	31 400	128	327	Bond at S. end
Av.	104	10 300	10 000	192	14 370	26 870	109	279	
84*	104	17 000	15 000	243	20 500	24 900	158	327	Bond at S. end.
203	91	13 000	11 200	185	19 300	23 500	149	309	Bond at S. end.
204	90	13 000	12 500	204	17 000	20 800	132	273	Bond at S. end.
Av.	95	14 300	12 900	211	18 900	23 070	146	303	
117	118	19 000	19 000	292	33 000	48 100	250	500	Bond at S. end.
62	56	12 000	.. ...	...	22 500	33 200	172	390	Diagonal tension and bond at S. end.
202	88	14 000	12 000	213	19 000	28 100	146	332	Bond at S. end.
Av.	72	13 000	....	....	20 750	30 650	159	361	
85	105	.. ...	6 000	128	28 700	72 500	209	568	Tension in steel.
118	118	20 000	15 000	233	32 100	46 700	241	488	Bond at S. end.

° Corresponding to a slip of 0.0002 in.
* The load was released and reapplied. See Art. 90 and Fig. 51.

71. *Bond with Deformed Bars.*—One beam in the 1909 series was reinforced with a 1-in. cup bar, one with a ¾-in. corrugated square bar (type B) and two with 1⅛-in. corrugated rounds. Beam No. 118 reinforced with a 1-in. twisted square bar will be referred to in the discussion of other beams of the same kind in the 1912 series (see Art. 84).

Beam No. 117, reinforced with one 1-in. cup bar, carried the highest load in this series—33 000 lb. End slip began at an applied load of 19 000 lb. and a computed bond stress of 292 lb. per sq. in. This is about the same load that caused the first diagonal crack. The maximum bond resistance was 500 lb. per sq. in., corresponding to a steel stress of 48 100 lb. per sq. in. The load-end-slip and load-deflection curves for this test are given in Fig. 77. The slip measured at the end where failure occurred was 0.006 in. at the maximum load; the slip at the opposite end was 0.001 in.

Beam No. 85, reinforced with one ¾-in. corrugated square bar (type B) showed first end slip at a computed bond stress of 128 lb. per sq. in. The load-slip curve for this beam (Fig. 77) shows a very rapid slip at one end following an applied load of about 7000 lb. The end slip had reached 0.001 in. at a load of 8000 lb.; at the maximum load the slip was about 0.02 in. at one end and 0.004 in. at the other. While this beam failed finally by tension in the steel, it is plain that a bond resistance much higher than the value given—568 lb. per sq. in.—could not have been developed.

Beams No. 62 and 202 were each reinforced with one 1⅛-in. corrugated round bar. Slip of bar was not measured in Beam No. 62. In Beam No. 202 end slip began at a load of 12 000 lb. and bond stress of 213 lb. per sq. in. After a load of 12 000 lb., slipping at both ends was very pronounced. At failure, at a load of 19 000 lb., bond stress of 332 lb. per sq. in., one end of the bar had slipped 0.014 in.; the other 0.007 in. The bond stress at the beginning of end slip of Beam No. 202 was about 5% higher than the average of the six beams in this series which were reinforced with plain rounds. The average bond stress at the maximum load for the two beams reinforced with 1⅛-in. corrugated rounds (361 lb. per sq. in.) was 24% higher than the average of the six beams with plain rounds. However, the beams with corrugated bars were tested at a somewhat earlier age; on the other hand the cube tests show them to be made of concrete of somewhat higher compressive strength than those with plain bars.

b. 1911 Beam Tests.

72. *Outline of Series.*—Thirty-six reinforced concrete beams were included in the 1911 series. Plain round and corrugated bars were used for longitudinal reinforcement. All the beams, except two, were tested with a 6-ft. span. Beam No. 1045.2 and 1045.3 were tested with an 8-ft. span. Several of the beams in this series were tested with ends overhanging the supports 9 in. or 15 in. In one group, the depth of concrete below the steel was varied. Fifteen of the beams had no web reinforcement; the remainder were provided with V-shaped stirrups of ¼-in. or ½-in. plain rounds. In the 1911 beams the concrete was hand-mixed; the age at test averaged about 8 months.

Pull-out specimens and 6-in. cubes were made from the same materials as were used in many of the beams. The pull-out specimens were stored in the open air with the beams, until tested; the cubes were stored in damp sand.

Details of the make-up of the beams, their dimensions, the materials used and the strength of the concrete will be found in Table 27. Table 28 gives the data of the tests and some of the calculated stresses in the beams as well as notes on failure. The computed bond stresses developed in the beams and in the pull-out tests in this series at various amounts of end slip will be found in Table 29. A summary of the bond stresses in the beam and pull-out tests is given in Table 30.

In several of the beams in this series measurements were made on slip of bar at points other than the ends. Discussion of the slip found at internal points will be given with the discussion of similar tests in the 1912 series (Art. 94).

73. *Basis of Comparison of Bond Resistance in Beam and Pull-out Tests.*—In the 1911 and 1912 beam series, the corresponding beams and pull-out specimens were made from the same batch and stored under the same conditions. In comparing the bond resistance in beam and pull-out tests, it is evident that the bond stresses corresponding to definite amounts of slip in each case should be considered. The amount of slip in both kinds of specimens was measured at the free end of the bar, and at other points in some of the beam tests. Differences in bond resistance developed in the two forms of test specimens may be expected to be due principally to differences in the secondary stresses in the

TABLE 27.

Data of Reinforced Concrete Beams—1911 Series.

1-2-4 hand-mixed concrete. The longitudinal reinforcement in each beam consisted of a single bar of high-carbon steel. All beams were 8 in. wide; total depth 12 in., unless otherwise noted; depth to center of steel, 10-in.

Group	Beam No.	Length feet	Longitudinal Reinforcement		Stirrups (Round Bars 6 in. apart)	Beam from same Batch	Cement	Mixture by Weight	Compression Tests of 6-in. Cubes*	
			Kind of Round Bar	Per cent					Age at Test, mo.	Average of 3 Tests lb. per sq. in.
1	1037.1	6½	1-in. plain	0.98	None	1032.1	Universal	1-2.10-3.67	9	2733
	1037.2	6½	1-in. plain	0.98	None	1039.2	Universal	1-2.08-3.46	8½	3977
	1037.3	6½	1-in. plain	0.98	None	1043.2	Universal	1-2.12-3.56	7	3647
	1040.3	6½	1-in. plain	0.98	None	1032.3	Lehigh	1-2.13-3.72	8½	2533
2	1039.1	6½	1-in. plain	0.98	¼-in.	1043.1	Universal	1-2.02-3.63	9	2610
	1039.2	6½	1-in. plain	0.98	¼-in.	1037.2	Universal	1-2.08-3.46	8½	3977
	1039.3	6½	1-in. plain	0.98	¼-in.	1035.3	Lehigh	1-2.06-3.62	7	4117
3	1031.1	6½	1-in. plain	0.98	½-in.	1034.1	Universal	1-2.11-3.67	9	3173
	1031.2	6½	1-in. plain	0.98	½-in.	1035.2	Universal	1-2.20-3.72	8	2307
	1032.1	6½	1-in. plain	0.98	½-in.	1037.1	Universal	1-2.10-3.67	9	2733
	1032.2	6½	1-in. plain	0.98	½-in.	1045.1	Universal	1-2.13-3.51	7½	3220
4	1031.3	6½	1-in. plain	0.98	½-in.	1037.3	Universal	1-2.12-3.56	7	3647
	1032.3	6½	1-in. plain	0.98	½-in.	1040.3	Lehigh	1-2.13-3.72	8½	2533
5	1044.1+	6½	1-in. plain	0.98	None	1044.5	Universal	1-2.05-3.40	7	3157
	1044.2+	6½	1-in. plain	0.98	None	1045.2	Lehigh	1-2.08-3.68	8½	2920
	1044.3+	6½	1-in. plain	0.98	None	1042.3	Lehigh	1-2.07-3.56	8	2800
6	1044.5•	6½	1-in. plain	0.98	None	1044.1	Universal	1-2.05-3.40	7	3657
	1044.6•	6½	1-in. plain	0.98	None	1045.3	Lehigh	1-2.08-3.51	8	2517
	1044.7•	6½	1-in. plain	0.98	None	......	Lehigh	1-2.03-3.77	...	....

* The average strength of 6-in. cubes tested at about 8 months was as follows: 11 sets from Universal cement, 3100 lb. per sq. in.; 6 sets from Lehigh cement, 2937 lb. per sq. in

+ Total depth 11 in.; depth to center of steel 10 in.

• Total depth 14 in.; depth to center of steel 10-in.

(*Table 27 continued on page 136*)

TABLE 28.

TESTS OF REINFORCED CONCRETE BEAMS—1911 SERIES.

The loads were applied at the one-third points of the span, unless otherwise noted.

Loads are given in pounds; stresses are given in pounds per square inch. In computing unit stresses the weight of the beam was considered.

Group	Beam No.	Length feet	Test Span feet	Over-hang at each End in.	Age at Test mo.	Load at First Outer Crack	At First Slip of End of Bar		At Maximum Load				Maximum Bond Resistance in Pull-out Tests	Failure of Beam
							Applied Load	Computed Bond Stress	Applied Load	Tensile Stress in Steel	Vertical Shearing Stress	Computed Bond Stress		
1	1037.1	6½	6	3	8	12 000	14 000	272	15 000	27 800	115	291	...	Diag. tension followed by bond.
	1037.2	6½	6	3	8	10 000	8 000	159	18 500	34 200	140	356	568	Sudden failure by bond, S. end.
	1037.3	6½	6	3	8½	10 000	15 000	291	21 400	39 300	162	410	...	Bond failure at S. end.
	1040.3	6½	6	3	7	10 000	12 000	235	18 900	34 800	143	363	373	Bond and diag. tens. at N. end.
	Average..	....	.....	.....	8	10 500	12 200	239	18 450	34 000	140	355	470	
2	1039.1	6½	6	3	8	10 000	12 000	235	17 300	32 000	132	334	457	Bond at S. end.
	1039.2	6½	6	3	8	8 000	14 000	272	27 800	50 800	209	529	568	Bond at S. end.
	1039.3†	6½	6	3	7½	12 000	20 000	384	26 000†	47 600	196	496†	687	Bond at S. end
	Average..	....	.....	.....	8	10 000	15 300	297	23 700	43 500	179	453	571	
3	1031.1	6½	6	3	8	8 000	11 000	216	15 900	29 500	123	307	477	Bond; bar pulled out at N. end.
	1031.2	6½	6	3	8	7 000	9 000	179	16 400	30 400	125	317	566	Bond followed by diag. tens.
	1032.1	6½	6	3	8	6 000	10 000	197	15 000	27 800	115	290	...	Bond at S. end.
	1032.2	6½	6	3	7	14 500	15 000	291	21 500	39 500	163	411	542	Bond at S. end.
	Average..	....	.....	.....	8	8 900	11 200	221	17 200	32 400	142	331	528	
4	1031.3*	6½	6	3	8	11 000	10 000	197	18 900	43 500	143	363*	...	Probably bond at S. end.
	1032.3*	6½	6	3	7	8 000	10 000	197	20 500	47 100	155	393*	373	Bond at S. end.
	Average..	....	.....	.....	7½	9 500	10 000	197	19 700	45 300	149	378	...	
5	1044.1	6½	6	3	7	12 000	17 000	327	20 000	36 800	152	383	371	Bond at N. end.
	1044.2	6½	6	3	7	12 000	14 000	272	17 800	32 800	135	345	...	Bond at N. end.
	1044.3	6½	6	3	7	8 000	12 000	234	17 850	32 900	136	344	...	Bond at S. end.
	Average..	....	.....	.....	7	10 700	14 300	274	18 550	34 200	141	357	...	
6	1044.5	6½	6	3	10	......	23 000	439	27 400	50 100	205	522	371	Bond at N. end.
	1044.6	6½	6	3	7	10 000	24 000	458	29 700	54 200	222	564	...	Bond at N. end.
	1044.7	6½	6	3	7	......	21 000	403	30 700	56 000	230	583	...	Bond at N. end.
	Average..	....	.....	.....	8	10 000	22 700	433	29 300	53 400	219	556	...	

† The load on Beam No. 1039.3 was maintained at 26 000 lb. until the bar pulled out; see Art. 90 and Fig. 52.

* Loaded at points 6 in. each side of middle.

(Table 28 continued on page 137)

TABLE 27—Continued from page 134.

Continued from page 134.

Data of Reinforced Concrete Beams—1911 Series.

1-2-4 hand-mixed concrete. The longitudinal reinforcement in each beam consisted of a single bar of high-carbon steel. All beams were 8 in. wide; total depth 12 in., unless otherwise noted; depth to center of steel, 10-in.

Group	Beam No.	Length feet	Longitudinal Reinforcement: Kind of Round Bar	Longitudinal Reinforcement: Per cent	Stirrups (Round Bars 6 in. apart)	Beam from same Batch	Cement	Mixture by Weight	Compression Tests of 6-in. Cubes: Age at Test, mo.	Compression Tests of 6-in. Cubes: Average of 3 Tests lb. per sq. in.
7	1042.1	7½	1-in. plain	0.98	½-in.	1035.1	Universal	1-2.12-3.63	9	2813
	1042.2	7½	1-in. plain	0.98	½-in.	1043.3	Lehigh	1-2.13-3.58	8½	2737
8	1043.1	8½	1-in. plain	0.98	None	1039.1	Universal	1-2.02-3.63	9	2610
	1043.2	8½	1-in. plain	0.98	None	1031.3	Universal	1-2.12-3.56	7	3647
9	1035.1	6½	1¼-in. plain	1.53	½-in.	1042.1	Universal	1-2.12-3.63	9	2813
	1035.2	6½	1¼-in. plain	1.53	½-in.	1031.2	Universal	1-2.20-3.72	8	2307
	1035.3	6½	1¼-in. plain	1.53	½-in.	1039.3	Lehigh	1-2.06-3.62	7	4117
10	1043.3	8½	1¼-in. plain	1.53	None	1042.2	Lehigh	1-2.13-3.58	8½	2737
	1045.1	8½	1¼-in. plain	1.53	½-in.	1032.2	Universal	1-2.13-3.51	7½	3220
11	1045.2	8½	1¼-in. plain	1.53	½-in.	1044.2	Lehigh	1-2.08-3.68	8½	2920
	1045.3	8½	1¼-in. plain	1.53	½-in.	1044.6	Lehigh	1-2.08-3.51	8	2517
12	1034.1	6½	1⅛-in. corrugated	1.24	½-in.	1031.1	Universal	1-2.11-3.67	9	3173
	1034.2	6½	1⅛-in. corrugated	1.24	½-in.	1040.1	Universal	1-2.13-3.85	8	2630
	1034.3	6½	1⅛-in. corrugated	1.24	½-in.	1040.2	Universal	1-2.13-3.52	8½	3807
13	1040.1	7½	1⅛-in. corrugated	1.24	None	1034.2	Universal	1-2.13-3.85	8	2630
	1040.2	7½	1⅛-in. corrugated	1.24	None	1034.3	Universal	1-2.13-3.52	8½	3807
	1042.3	7½	1⅛-in. corrugated	1.24	½-in.	1044.3	Lehigh	1-2.07-3.56	8	2800

° The average strength of 6-in. cubes tested at about 8 months was as follows: 11 sets from Universal cement, 3100 lb. per sq. in.; 6 sets from Lehigh cement, 2937 lb. per sq. in.

TABLE 28—CONTINUED FROM PAGE 135.

TESTS OF REINFORCED CONCRETE BEAMS—1911 SERIES.

The loads were applied at the one-third points of the span.

Loads are given in pounds; stresses are given in pounds per square inch. In computing unit stresses the weight of the beam was considered.

Group	Beam No.	Length feet	Test Span feet	Over-hang at each End in.	Age at Test mo.	Load at First Outer Crack	At First Slip of End of Bar		At Maximum Load				Maximum Bond Resistance in Pull-out Tests	Failure of Beam
							Applied Load	Computed Bond Stress	Applied Load	Tensile Stress in Steel	Vertical Shearing Stress	Computed Bond Stress		
7	1042.1	7½	6	9	8	8 000	20 500	394	25 600	46 800	193	488	375	Bond at S. end.
	1042.2	7½	6	9	11	11 000	19 000	365	26 900	49 200	202	511	...	Bond at S. end.
	Average	......	....	....	9½	9 500	19 750	379	26 250	48 000	197	500	...	
8	1043.1	8½	6	15	8	14 600	20 000	384	23 600	43 200	178	451	457	Diag. tens. followed by bond.
	1043.2	8½	6	15	8½	10 000	26 000	496	26 200	48 000	197	498	...	Diag. tens. at S. end.
	Average	......	....	....	8	12 300	23 000	440	24 900	45 600	187	475	...	
9	1035.1	6½	6	3	8	12 000	14 000	226	19 200	23 300	149	307	395	Bond at N. end.
	1035.2	6½	6	3	8	8 000	10 000	165	21 100	25 500	163	336	480	Bond at S. end.
	1035.3	6½	6	3	7	12 000	14 000	226	38 000	45 500	291	598	536	Diag. tens. followed by bond.
	Average	......	....	....	7½	10 700	12 700	206	26 100	31 400	201	413	470	
10	1043.3	8½	6	15	10½	12 000	22 000	351	22 500	27 200	174	358	...	Diagonal tension.
	1045.1	8½	6	15	7	12 000	28 000	444	36 400	43 600	271	572	542	Diag. tens. followed by bond.
	Average	......	....	....	9	12 000	25 000	397	29 450	35 400	226	465	...	
11	1045.2	8½	8	3	11	8 000	18 000	288	23 900	38 600	186	380	...	Bond at N. end.
	1045.3	8½	8	3	10	8 000	14 000	227	23 500	38 200	182	374	...	Bond at N. end.
	Average	......	....	....	10½	8 000	16 000	257	23 700	38 400	184	377	...	
12	1034.1	6½	6	3	8	14 000	14 000	245	28 200	41 200	214	486	1374	Bond at N. end.
	1034.2	6½	6	3	7	10 000	14 500	255	25 000	36 600	190	432	1444	Bond at N. end.
	1034.3	6½	6	3	9	10 000	10 000	179	33 600	49 000	251	577	471	Bond and diag. tens. at both ends.
	Average	......	....	....	8	11 300	12 800	226	28 900	42 300	219	498	...	
13	1040.1	7½	6	9	7	13 400	18 000	314	25 500	37 300	194	441	1444	Diag. tens. followed by bond.
	1040.2	7½	6	9	8	10 000	21 000	364	27 700	40 500	210	478	471	Diagonal tension.
	1042.3	7½	6	9	7	10 000	28 000	483	32 500	47 300	246	559	...	Tension in steel.
	Average	......	....	....	7½	11 100	22 400	387	28 600	41 700	217	493	...	

TABLE 29.

Comparison of Bond Resistance in Beams and Pull-out Tests—1911 Series.

The measurements of slip of bar in the beam tests refer to the end showing the greater slip.
The bond stresses given for the pull-out specimens are the average of three tests on bars embedded 8 in.
Stresses are given in pounds per square inch.

Group	Beam No.	Size and Kind of Round Bar	BEAM TESTS: Age at Test mo.	Bond Stress at End Slip of (inches)					Computed Bond Stress at Maximum Load	PULL-OUT TESTS: Age at Test mo.	Bond Stress at End Slip of (inches)							Maximum Bond Resistance
				.0002	.0005	.001	.002	.005			.0002	.0005	.001	.002	.005	.010	.020	
	1037.1	1-in. plain	8	272	280	...	...	...	291	.	...	...	...	...	...	...	...	...
1	1037.2	1-in. plain	8	159	291	340	...	...	356	9	280	348	398	449	518	555	556	568
	1037.3	1-in. plain	8½	291	365	394	...	...	410	.	...	...	...	...	...	...	...	...
	1040.3	1-in. plain	7	235	330	...	...	...	363	7	194	233	254	285	338	363	368	373
	Average		8	239	316	...	...	...	352	8	237	290	326	367	428	459	462	470
	1039.1	1-in. plain	8	235	272	310	319	280	334	6	224	281	334	374	437	456	437	457
2	1039.2	1-in. plain	8	275	367	479	510	525	531	9	280	348	398	449	518	555	556	558
	1039.3	1-in. plain	7½	421	478	496	...	...	496	8	355	491	557	598	632	668	667	687
	Average		8	310	372	428	...	...	454	8	286	373	430	474	529	560	553	567
	1031.1	1-in. plain	8	190	200	233	255	280	307	5	235	289	345	394	461	470	465	477
3	1031.2	1-in. plain	8	189	235	253	281	...	317	8	210	316	393	468	543	566	551	566
	1032.1	1-in. plain	8	197	220	231	253	280	290	.	...	...	...	...	...	...	...	...
	1032.2	1-in. plain	7	291	328	345	383	402	411	9	306	379	436	484	529	540	530	542
	Average		8	217	246	266	293	...	331	7½	250	328	391	448	511	525	515	525
4	1031.3	1-in. plain	8	197	309	356	...	...	363	.	...	...	...	...	...	...	...	...
	1032.3	1-in. plain	7	197	291	347	374	393	393	7	194	233	254	285	338	363	368	373
	Average		7½	197	300	351	...	...	378	.	...	...	...	...	...	...	...	...
	1044.1	1-in. plain	7	300	347	364	383	...	383	6	191	230	274	303	352	365	346	371
5	1044.2	1-in. plain	7	272	328	340	...	...	345	.	...	...	...	...	...	...	...	...
	1044.3	1-in. plain	7	233	315	330	340	344	344	.	...	...	...	...	...	...	...	...
	Average		7	268	330	345	...	...	357	.	...	...	...	...	...	...	...	...
	1044.5	1-in. plain	10	439	445	460	485	512	522	6	191	230	274	303	352	365	346	371
6	1044.6	1-in. plain	7	458	520	533	542	561	566	.	...	...	...	...	...	...	...	...
	1044.7	1-in. plain	7	403	478	530	541	580	583	.	...	...	...	...	...	...	...	...
	Average		8	433	481	508	523	551	557	.	...	...	...	...	...	...	...	...

TABLE 29—Continued.

Comparison of Bond Resistance in Beams and Pull-out Tests—1911 Series.

Group	Beam No.	Size and Kind of Round Bar	Beam Tests: Age at Test mo.	Beam Tests: Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	Beam Tests: Computed Bond Stress at Maximum Load	Pull-out Tests: Age at Test mo.	Pull-out Tests: Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	.010	.020	Pull-out Tests: Maximum Bond Resistance
7	1042.1	1-in. plain..........	8	394	425	459	480	...	488	8	160	180	208	248	329	364	372	375
	1042.2	1-in. plain..........	11	365	402	430	444	486	511	.	...	...	...	...	...	...	...	...
	Average	....	9½	380	414	445	462	...	500	.	...	...	...	...	...	...	...	...
8	1043.1	1-in. plain..........	8	384	421	410	420	403	451	6	224	281	334	374	437	456	437	457
	1043.2	1-in. plain..........	8½	496	...	498	477	498	498	.	...	...	...	...	...	...	...	...
	Average	....	8	440	...	454	...	440	474	.	...	...	...	...	...	...	...	...
9	1035.1	1¼-in. plain........	8	226	230	...	240	307	307	8	160	180	208	248	328	364	372	375
	1035.2	1¼-in. plain........	8	165	227	258	273	319	336	7	204	326	398	449	478	...	424	480
	1035.3	1¼-in. plain........	7	227	319	400	549	...	596	7½	284	368	419	467	502	526	515	536
	Average	....	7½	206	259	...	354	...	413	7½	216	291	342	404	436	...	455	495
10	1043.3	1¼-in. plain........	10½	350	358	...	...	...	358	.	...	...	...	...	...	...	...	...
	1045.1	1¼-in. plain........	7	444	474	515	534	555	572	7	306	379	436	484	529	540	530	542
	Average	....	9	397	416	...	...	...	465	.	...	...	...	...	...	...	...	...
11	1045.2	1¼-in. plain........	11	288	351	366	...	...	378	9	306	379	436	484	529	540	530	542
	1045.3	1¼-in. plain........	10	227	289	340	358	365	374	9	306	379	436	484	529	540	530	542
	Average	....	10½	267	320	353	...	...	376	9	306	379	436	484	529	540	530	542
12	1034.1	1⅛-in. corrugated...	8	245	290	320	350	412	482	9	121	162	216	300	456	571	774	1374*
	1034.2	1⅛-in. corrugated...	7	240	260	296	313	363	430	7	222	289	363	404	450	491	585	1444*
	1034.3	1⅛-in. corrugated...	9	179	264	330	367	430	576	7	201	275	320	351	389	412	418	471
	Average	....	8	221	271	317	343	402	496	7½	181	242	300	352	432	491	592	1096
13	1040.1	1⅛-in. corrugated...	7	314	360	410	433	400	441	7	222	289	363	404	450	491	585	1444*
	1040.2	1⅛-in. corrugated...	8	364	435	450	475	...	478	7	201	275	320	351	389	412	418	471
	1042.3	1⅛-in. corrugated...	7	483	520	559	...	...	559	.	...	...	...	...	...	...	...	...
	Average	....	7½	387	438	473	...	...	493	7	211	282	341	377	419	451	501	907

* Blocks reinforced with 6 turns of ¼-in. wire in the form of a spiral.

specimen and in a much less degree to the form of the specimen. The anti-stretch slip mentioned in a preceding paragraph is a manifestation of one of the secondary stresses. Since the beams were loaded symmetrically and failure was practically always due to bond or some cause involving bond, the bar pulled out at the end where the bond resistance was the weaker. In other words the beam tests give in each case the smaller of two possible values of bond resistance resulting from the same combination of materials. In a few tests one end of the bar showed a greater slip during the earlier stages of loading, only to be overtaken by the other end as the loading progressed. In two or three tests both ends of the beam behaved almost identically in this respect. These observations apply to beams reinforced both with plain and deformed bars. The pull-out tests for comparison with the reinforced concrete beams were made in sets of three.

Since we have automatically rejected the higher of the two bond resistances in the beams, it will make the comparison more nearly correct to reject the highest one of the pull-out specimens. The average values for the lowest two from each set of pull-out specimens are given in Tables 29 and 30. These are the values which have been used for comparison in the discussion of beam and pull-out tests. It will be seen that this method gives values for the pull-out tests which are a little too high; but the error due to this cause is not of enough consequence to justify further refinement in the computations.

74. *Bond with Plain Round Bars.*—In the 1911 series 23 beams were reinforced with 1-in. plain rounds and 7 beams with 1¼-in. plain rounds. The effect of size of bar, vertical stirrups, depth of concrete below the steel, overhang of ends, etc., in beams reinforced with plain rounds will be discussed in detail in the following articles. It will be seen later that the presence of vertical stirrups has no considerable effect on the bond resistance of beams of this kind, hence for purposes of the present discussion all beams in the 1911 series reinforced with 1-in. plain round bars, except those having a total depth of 14 in. and those with unusual overhang of ends, will be grouped together.

The groups with 1-in. plain rounds include 16 tests as shown in groups 1 to 5, Table 30. End slip became appreciable at a bond stress of 247 lb. per sq. in., 67% of the maximum bond resistance. The largest amount of end slip which was observed in every test in these groups was 0.001 in., corresponding to a bond stress of 344 lb. per sq. in., 92% of

TABLE 30.

SUMMARY OF BOND STRESSES IN BEAM AND PULL-OUT TESTS—1911 SERIES.

Stresses are given in pounds per square inch.

Group	Characteristics	No. of Tests	Age at Test mo.	Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	.01	Computed Bond Stress at Maximum Load
	Beam Tests; 1-in. Plain Rounds.									
1-5	All beams except as noted*	16	7½	247	310	344	.....	.....	.....	371†
7	Beams with 9-in. overhang	2	9½	380	414	445	462	.....	.....	500
8	Beams with 15-in. overhang	2	8	440	.....	454	.....	440	.....	474
6	Beams 14 in. total depth	3	8	433	481	508	523	.....	.....	557
	Pull-Out Tests; 1-in. Plain Rounds.									
1-8	Lowest two from each set of three tests°	14	.....	225	298	353	399	457	481	493
	All pull-out tests	21	7	242	312	365	410	469	491	500
	Highest from each set	7	.....	275	340	390	433	491	509	511
	Lowest from each set	7	.....	201	284	338	385	430	475	491
	Beam Tests; 1¼-in. Plain Rounds.									
9	6-ft. beams with 3-in. overhang	3	7½	206	259	.....	354	.....	.....	413
10	8-ft. beams with 3-in. overhang	2	8½	397	416	.....	.....	.....	.....	465
11	6-ft. beams with 15-in. overhang	2	10½	267	320	353	.....	.....	.....	376
	Pull-out Tests; 1¼-in. Plain Rounds.									
9-11	Lowest two from each set of 3 tests°	8	.....	231	301	342	389	446	.....	474
	All pull-out tests	12	8	239	313	365	412	459	483	483
	Highest from each set	4	.....	253	338	413	459	487	.....	502
	Lowest from each set	4	.....	226	266	313	360	410	.....	441
	Beam Tests; 1⅛-in. Corrugated Rounds.									
12	Beams with 3-in. overhang	3	8	221	271	317	343	402	....	496
13	Beams with 9-in. overhang	3	7½	387	438	473	.....	.....	.....	493
	Pull-out Tests; 1⅛-in. Corrugated Rounds.									
12, 13	Lowest two from each set of 3 tests°	6	.....	184	233	270	313	400	440	✦
	All pull-out tests	9	7½	181	242	300	354	432	491	✦
	Highest from each set	3	.....	141	262	360	464	526	598	✦
	Lowest from each set	3	.....	190	242	280	312	367	409	✦

* Includes all beams reinforced with 1-in. plain rounds, except those in groups 6, 7 and 8.

† The maximum bond resistance for 5 beams made from Lehigh cement averaged 390 lb. per sq. in. See cube tests, Table 27.

° Use these values for comparison with bond stresses in beam tests. See Art. 73.

✦ Omitted on account of part of the specimens being reinforced against bursting and part unreinforced. See Table 29 for details of these tests.

the maximum bond resistance. It is evident that when the end slip of the bar has reached 0.001 in. the stress distribution is such that the beam generally has passed its usefulness for carrying load.

In the case of five beams reinforced with 1¼-in. plain rounds (Table 30) end slip began at a computed bond stress of 282 lb. per sq. in., 65% of the maximum resistance. In this group an end slip of 0.0005 in. was measured in all the tests, corresponding to a bond stress of 86% of the maximum bond resistance.

A comparison of the bond stresses developed in the beams reinforced with 1-in. and 1¼-in. plain rounds in Table 30 and Fig. 49 with the pull-out tests on bars of the same sizes (the average of the lowest two tests from each set) shows values for the two kinds of tests which are similar at each amount of slip given in the table up to an end slip of about 0.001 in. The maximum bond resistance for the beams in these two groups is about the same as the bond stress developed in the corresponding pull-out specimens at a slip of 0.002 in. Fig. 78 shows the load-deflection and load-slip curves for typical beams reinforced with plain round bars. The tests do not show any material difference in bond unit resistance due to size of bar.

A summary of the bond stresses developed in all the 6-ft. beams reinforced with plain round bars and loaded at one-third points is given in Table 35.

75. *Effect of Vertical Stirrups on Bond Resistance.*—Beam groups 1, 2 and 3, in Table 28, may be used to see whether the presence of vertical stirrups influences bond resistance in beams of this kind. The beams in group 1 had no stirrups; those in groups 2 and 3 were reinforced throughout the outer thirds with V-shaped stirrups of ¼-in. and ½-in. rounds, respectively, spaced 6 in. apart as shown in Fig. 2 (b). Each of these beams was reinforced with one 1-in. plain round, and was tested on a 6-ft. span. The relation of bond resistance due to the presence of web reinforcement is not well defined. The beams with ¼-in. stirrups gave higher values for bond resistance at all stages of the tests than either of the other groups. In all these tests end slip of bar became appreciable at about 65% (range 64% to 67%) of the ultimate load. At an end slip of 0.0005 in. the average bond resistance of the beams is 82% of the ultimate. It will be seen in Tables 27 and 28 that both the cube tests and pull-out tests for the beams in group 2 indicate a better quality of concrete than that in the beams of groups

1 and 3. The results indicate that bond stress is the primary cause of failure in all these tests. Although the diagonal tensile stresses were fairly high, it would appear that if the reinforcement had not slipped, failure by diagonal tension would not have occurred until a higher load had been applied. Of course stirrups of this kind may not be expected to be effective when the bond stresses are high. Attention is called to the discussion in Art. 78.

Load deflection and load-slip curves for beams with and without stirrups are given in Fig. 78 and 79. The appearance of some of the beams after failure is shown in Fig. 57.

76. *Effect of Depth of Concrete below the Reinforcement.*—In general, the depth of concrete below the center of the longitudinal reinforcement was 2 in. In two groups of tests this depth was made 1 in. and 4 in., respectively; that is, the total depth of the beams was 11 and 14 in., with the depth from top of beam to center of bar 10 in., as usual. These beams were not provided with vertical stirrups; they were each reinforced with one 1-in. plain round bar and were tested on a 6-ft. span. See groups 5 (1-in. depth), 1 (2-in. depth) and 6 (4-in. depth), Table 28. It is seen that there is little difference in the values for the beams with depths of 1 and 2 in., but the beams with 4 in. of concrete below the steel show a very great increase in strength. The maximum bond resistance for the 1-in. and 2-in. depth averaged 356 lb. per sq. in., while for the 4-in. depth the maximum was 557 lb. per sq. in. The load-deflection and load-slip curves for these beams are given in Fig. 78. The deflection of beam is greatest for the beams with 1-in. thickness and least for those with 4-in. thickness. Beams in group 6 show great stiffness up to a load of about 6000 lb. The photograph, Fig. 58a, shows the appearance of these beams after test. The numbers opposite the cracks indicate the growth of the cracks at loads expressed in thousands of pounds. An interesting feature of the tests in group 6 is the absence of cracks in the outer thirds of the beam length. It seems evident that the anti-stretch slip has occurred from the cracks near the load points and that slip has progressed outward from these cracks toward the ends of the beam during the remainder of the test instead of from the several cracks which usually appear in the outer thirds subsequently in the tests. The first end slip came at a materially higher load in this group. It seems probable that the distribution of

bond stress along the bar beyond the outer cracks in this case is not materially different from that found in a pull-out test. The full bond resistance for the embedded length of bar beyond the crack is developed, or at least that for a small amount of slip, instead of having part of the bond resistance consumed by stresses in opposite directions due to anti-stretch slip. The presence of the large mass of concrete below the bar acts to maintain the integrity of the concrete; its total tensile strength is greater than the available residual resistance to slip along the bar, and hence the concrete will slip along the bar, probably still maintaining some tensile stress. In the case of a small depth of concrete the total tensile strength of the concrete is insufficient to overcome the bond resistance, the concrete breaks in tension at another point and springs back both ways from the point of rupture, forming a crack. With further addition of load further slip will occur at the crack, and with still more load other cracks may appear. In this case a part of the bond resistance is consumed by stresses in opposite directions due to anti-stretch slip and due to the slip the bond resistance utilized is less.

For the beams of ordinary depth in groups 1 to 5 in Table 28 the outer cracks at the ends where failure occurred cross the plane of the steel at distances ranging from about 12 to 22 in. (average 17 in.) from the end of the beam. For the beams in group 6 with 4 in. of concrete below the center of the reinforcement, the principal failure cracks came at 21 to 30 in. (average 26 in.) from the end of the beam. It would appear that after the cracks have lengthened, the main effective bond resistance lies on the part of the bar between the outermost crack and the end of the beam.

77. *Effect of Span Length.*—The beams in group 11, Table 28, were loaded with an 8-ft. span. The beams were reinforced with 1¼-in. plain round bars and ½-in. vertical stirrups. These tests may be compared with the beams in group 9, loaded on a 6-ft. span. In the 6-ft. beams the first outer cracks appeared at an average load of 10 700 lb., and the first end slip of bar at 12 700 lb.; the corresponding loads for the 8-ft. beams were 8000 lb. and 16 000 lb., respectively. These loads are significant. The first outer crack appeared in both groups of beams at loads corresponding to a stress of about 13 500 lb. per sq. in. in the longitudinal steel at mid-span. The steel stresses at mid-span at beginning of slip at the end of the bar are about 15 600 and 26 000 lb. per sq. in. for the 6-ft. and 8-ft. beams, respectively, corresponding to

a computed bond stress of 206 and 257 lb. per sq. in. The average distances of the cracks from the ends of the beams were about 17 in. and 25 in., respectively. This suggests that when end slip of bar began the main effective bond resistance for beams of both lengths lies principally in the portion of the bar having an ubroken embedment. The fact that the maximum bond resistance for the 8-ft. beams is lower than for the 6-ft. beams is probably due to the opening of other outer cracks than the first one, nearer the supports, causing a further concentration of the bond resistance toward the ends of the bar.

Tests of other beams in which the span length varied are discussed in Art. 86.

78. *Effect of Length of Overhang of Ends of Beam.*—It has been the practice at the University of Illinois in designing test beams of the kind described herein to make the beam 6 in. longer than the test span. In making the usual calculations of bond stress no allowance has been made for this additional 3 in. of embedment of the reinforcing bar. In order to study the effect on bond resistance, some of the beams in the 1911 series were tested with the ends overhanging the supports for 9 in. or 15 in., as shown in Fig. 2 (c) and with the bars extending to the ends of the beams. 1-in. and 1¼-in. plain rounds and 1⅛-in. corrugated rounds were used in these tests; see groups 7, 8, 10 and 13 in Table 28. Figs. 58 and 59 show representative beams after failure. A summary of the tests is given in Table 30. These beams differed somewhat in web reinforcement, even in the same groups, and these differences must be kept in mind in making comparisons.

The effect of varying the length of overhang may be seen by comparing the values for the different functions given in Table 28 and also the bond stresses corresponding to different amounts of end slip in the beam and pull-out tests in Table 30. The applied loads at first outer crack show whether the appearance of anti-stretch slip was affected by overhang. The applied loads and the bond stresses developed at first end slip and at the maximum load indicate the influence of the overhang on the bond resistance of the beams.

One-inch plain rounds were used in beams with the ends overhanging the supports 3, 9 and 15 in. The tests with 3-in. overhang include 16 beams; the others two or three each. 1¼-in. plain rounds were used in beams with 3 in. and 15 in. overhang, and 1⅛-in. corru-

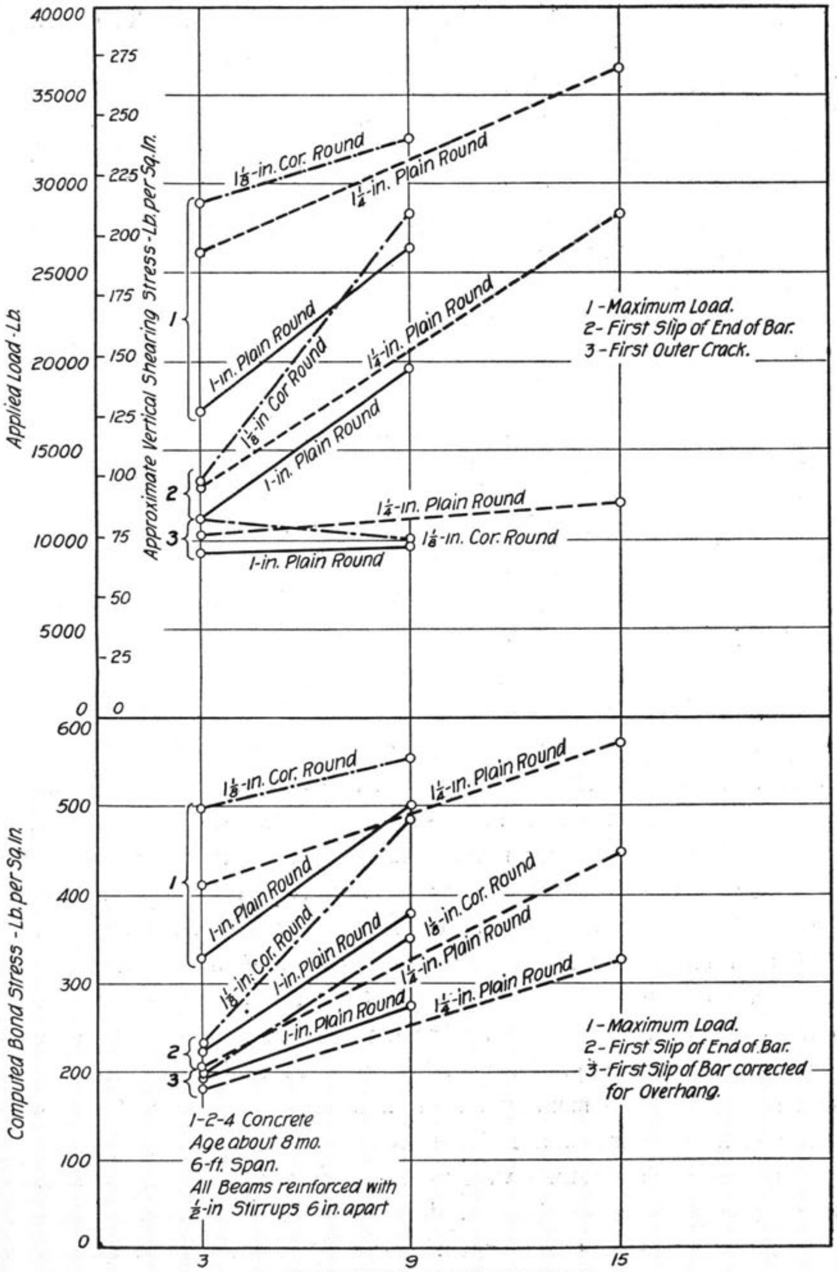


FIG. 48. EFFECT OF LENGTH OF OVERHANG OF ENDS OF BEAMS.

gated rounds in beams with 3 and 9 in. overhang. The values for bond stress given for these beams in the tables have all been computed in the same way without reference to the length of overhang of the ends.

A study of the data shows that the amount of the overhang of the ends had practically no influence on the load causing the opening of the first outer cracks and that the load at which first outer cracks appeared was independent of the kind and size of bar. The load at which first end slip of bar was found was greatly influenced by the length of overhang. In beams without stirrups the additional overhang seems to have little, if any, effect upon resistance to diagonal tension. For the beams recorded as failing in diagonal tension, the vertical shearing stress averaged 178 lb. per sq. in. for beams without stirrups and 288 lb. per sq. in. for beams with stirrups.

The relation between the bond stresses is somewhat different from that of the shearing stresses on account of the different diameters of the bars used. In Fig. 48 the values of the computed bond stresses have been plotted for the beams which were reinforced with vertical stirrups. It will be seen that the beams with 9-in. and 15-in. overhang developed a considerably higher computed bond stress than the beams with 3-in. overhang. If we reduce the computed bond stresses in these beams by considering that the bond stress at any load is uniformly distributed over the overhanging portion of the bar in the same way as is assumed for the outer thirds of the span (equivalent to multiplying the computed bond stress in beams with 3-in. overhang by 24/27, that in beams with 9-in. overhang by 24/33, and that in beams with 15-in. overhang by 24/39), it will be found that such corrected bond stresses will generally be greater for the longer overhangs. It should be noted that this method of correcting the bond stresses is subject to error in one respect, since slip was measured at the ends of the bars in all cases. The beginning of end slip with 15-in. overhang may be expected to represent quite a different state of stress in the beam proper than exists in a beam with 3-in. overhang when end slip begins.

79. *Bond on Corrugated Bars.*—1⅛-in. corrugated round bars were used for longitudinal reinforcement in 6 beams of the 1911 series—groups 12 and 13. These tests were referred to in the preceding articles; they will be included also in the discussion of similar tests from the 1912 beam series, Art. 85.

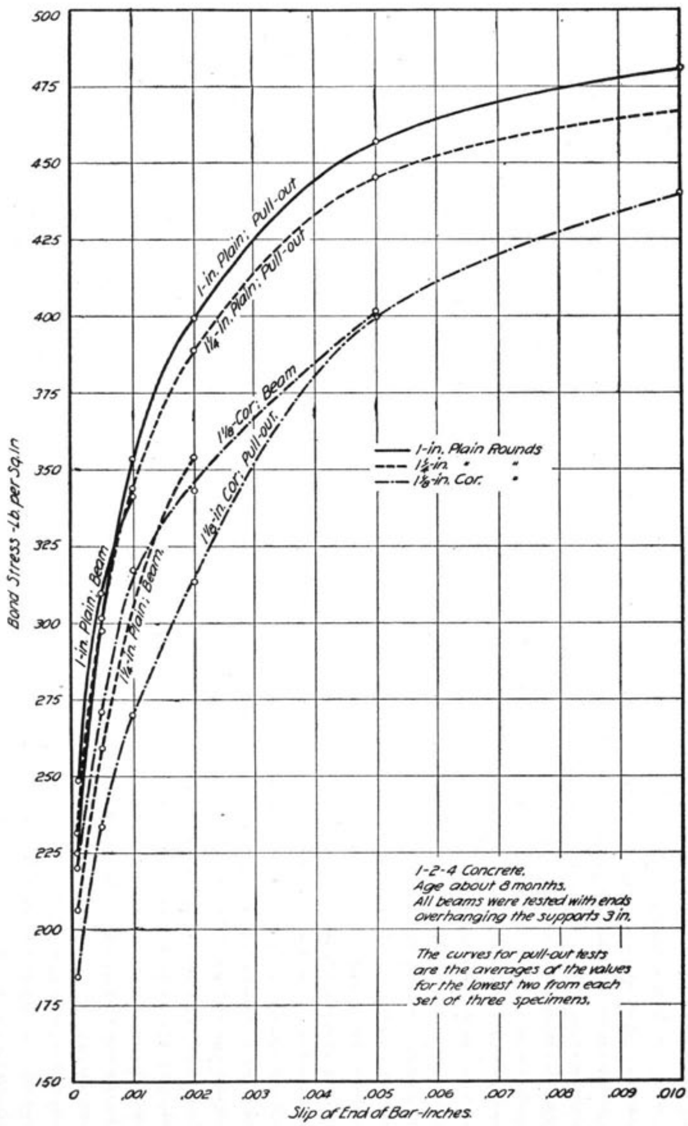


FIG. 49. COMPARISON OF BOND STRESSES IN BEAMS AND PULL-OUT SPECIMENS—1911 SERIES.

80. *Bond Resistance in 1911 Beam and Pull-out Tests.*—Table 30 gives a summary of the bond stresses in the 1911 beam and pull-out tests. The load-slip curves for many of these groups have been plotted in Fig. 49. As noted in Art. 73 the average stresses from the lowest two from each set of three pull-out specimens is used in all comparisons between the beam and pull-out tests. For the 1-in. plain rounds in beams with 3 in. overhang the bond stress up to an end slip of 0.001 in. is about the same as for the pull-out specimens for the same end slip. The bond stress at an end slip of 0.001 in. is 93% of the maximum bond resistance for the beam tests and 72% for the pull-out tests. The 1 and 1¼-in. plain rounds give nearly identical values in the pull-out tests. It should be borne in mind that with the uneven distribution of bond stress developed in beam tests the bond stress developed with a given end slip is dependent upon the relative dimensions of bar and beam and hence that the relation between the values of bond in beam tests and in pull-out tests here given may be to a certain extent accidental.

In the tests with 1¼-in. plain rounds the 6-ft. beams with 3-in. overhang gave values which are somewhat lower than the values from the pull-out specimens at the earlier stages of the tests; at the maximum load the average computed beam bond stress is 87% of the maximum bond resistance found in the pull-out tests.

For the 1⅛-in. corrugated round bars the bond stresses in the beam tests at end slips up to 0.005 in. are higher than in the pull-out tests for the same end slip. The maximum bond stresses in the two forms of specimen can not be compared directly, since part of the pull-out specimens were reinforced against bursting; in the one set not so reinforced the maximum bond resistance was 471 lb. per sq. in. as compared with 496 lb. per sq. in. in the beam tests. The corrugated bars in the beam tests give stresses which are about intermediate between those for the 1-in. and the 1¼-in. plain rounds for end slip less than about 0.002 in. The maximum bond resistance for the corrugated bars is about 25% higher than for the plain rounds.

Considering the pull-out tests only, the plain rounds give higher bond resistances than the corrugated rounds for all stages of the test up to the end slip which corresponds to the maximum bond resistance in the plain bars. A discussion of the relation of bond resistance in beams and pull-out specimens from another series of tests is given in **Art. 92.**

c. 1912 Beam Tests.

81. *Outline of Series.*—Sixty-three reinforced concrete beams were included in the 1912 series. Generally the span length was 6 ft.; one group of beams was tested on each of the following spans: 5, 7 and 8 ft.; four groups were tested on a 10-ft. span. The loads were generally applied at the one-third points; groups of 6-ft. beams were tested with two symmetrical loads spaced the following distances apart: 2, 2½, 3, 3½ and 4 ft. Plain round, plain square, twisted square, and corrugated round bars were used for longitudinal reinforcement. In all but six of the beams the longitudinal reinforcement consisted of a single bar. Three beams were reinforced with four ⅝-in. and three with three ¾-in. plain rounds.

The beams in this series were made in groups of three; the first beam in each group was made of hand-mixed concrete, the remainder of machine-mixed concrete. All the beams were provided with vertical stirrups of ½-in. rounds. In the beams reinforced with a single longitudinal bar, the stirrups were V-shaped; in the other beams U-shaped stirrups were used. See Fig. 2. The average age at test was 63 days.

Pull-out specimens and 6-in. cubes were made with nearly all of the beams. The pull-out specimens were stored in the open air with the beams; the cubes were stored in damp sand.

Details of the make-up of the beams, their dimensions, the materials used and data on the strength of the concrete will be found in Table 31. Table 32 gives data of the tests and some of the calculated stresses in the beams, as well as notes on the failures. The bond stresses corresponding to given amounts of end slip for both beam and pull-out tests will be found in Table 33. A summary of the bond stresses developed in this series of tests is given in Table 34.

In comparing the results of pull-out tests for the square, twisted and the deformed bars in this series with those made earlier it should be borne in mind that the concrete cylinders in this series were not reinforced against bursting.

82. *Bond Resistance with Plain Round Bars.*—Thirty-seven beams in the 1912 series were reinforced with 1-in. plain round bars. The tests to determine the effect of span length, effect of variation in the position of the loads, and on the sizes of bar are discussed elsewhere.

Table 35 gives a summary of the results of tests of 6-ft. beams reinforced with 1 and 1¼-in. plain round bars from the series of 1909, 1911 and 1912. The 1909 tests gave lower values than the other series, but the concrete was of lower strength, as may be seen from the cube tests. All but one of the beams included in this table failed in bond. Disregarding the differences in the age of the beams, the mean values for bond resistances are found as given in the table. First slip of bar was measured at the end of the beam at a mean bond stress of 236 lb. per sq. in.—66% of the maximum bond resistance. The mean bond stress at an end slip of 0.001 in. for the beams in these three series was 324 lb. per sq. in.—91% of the maximum bond resistance. The mean maximum bond resistance for the 34 beams considered was 356 lb. per sq. in. These values seem to be representative for the conditions present in the tests. However, it should be noted that the bond resistance developed in beams, as given by the ordinary methods of computation, appears to be dependent upon the relation of size of bar to the dimensions of the beam and to the span length and that the computed values found in these tests may not apply to bars of smaller diameters or to beams of other size and span.

83. *Bond Resistance with Plain Square Bars.*—Six beams were reinforced with 1-in. plain square bars. In group 29 the bars were placed with their sides horizontal; in group 30 the bars were placed with a diagonal line horizontal. Comparing the bond stresses in the beam and pull-out tests for groups 29 and 30 in Table 32 and in the summary, Table 34, it will be seen that while the bars placed with a diagonal horizontal give a higher bond resistance, the pull-out and cube tests show that on the average the concrete in the second group of tests was inferior in strength to that in the first group. Beam No. 1046.5 gave abnormally low bond resistance. It is probable that no difference in bond resistance can be ascribed to the difference in the position of the bars.

The bond stresses at various end slips in the beams reinforced with 1-in. square bars are about 75% of those for similar beams reinforced with 1-in. rounds. See groups 14-15 and 29 and 30, Tables 32 and 34. A comparison of the pull-out tests gives about the same relation. End slip of bar begins in the pull-out tests at a lower stress than in the beam tests; at a slip of 0.001 in. the stresses are about the same. At the maximum loads the calculated bond stresses in the beams average 86% of those in the pull-out tests. This is about the same ratio as for the tests with 1-in. round bars in this series.

TABLE 31.

Data of Reinforced Concrete Beams—1912 Series.

1-2-4 concrete; Universal portland cement, sand, and crushed limestone. The concrete for the first beam of each group was mixed by hand; all others were machine-mixed.

All beams were 8 in. wide; total depth 12 in.; depth to center of steel, 10 in.

Each beam, except those in Groups 27 and 28, was reinforced with a single longitudinal bar. All beams were provided with vertical stirrups of ½-in. plain rounds, spaced 6-in. apart, outside the load points. See Fig. 2 (f).

Group	Beam No.	Length feet	Longitudinal Reinforcement		Beam from same Batch	Mixture by Weight	Compression Tests of 6-in. Cubes*	
			Size and Kind of Bar	Per cent			Age days	Average of 3 Tests lb. per sq. in.
14	1052.1	6½	1-in. plain round...........	0.98	1051.1	1-1.95-3.34	70	2120
	1052.2	6½	1-in. plain round...........	0.98	......	1-1.95-3.34	61	2730
	1052.3	6½	1-in. plain round...........	0.98	1057.3	1-1.93-3.23	..	....
15	1056.1	6½	1-in. plain round...........	0.98	1057.1, 1058.1	1-1.94-3.29	62	2140
	1056.2	6½	1-in. plain round...........	0.98	......	1-2.00-3.20	68	3500
	1056.3	6½	1-in. plain round...........	0.98	1047.2	1-2.00-3.36	..	....
16	1052.4	6½	1-in. plain round 4 ⅜-in. auxiliary bars at each end of beam....	0.98	1055.1	1-2.07-3.48	61	2065
	1052.5	6½		0.98	......	1-1.92-3.20	66	2640
	1052.6	6½		0.98	1058.3	1-1.93-3.32	60	2960
17	1057.1	6½	1-in. plain round...........	0.98	1056.1, 1058.1	1-1.94-3.29	62	2140
	1057.2	6½	1-in. plain round...........	0.98	......	1-1.98-3.34	..	....
	1057.3	6½	1-in. plain round...........	0.98	1052.3	1-1.93-3.23	..	....
18	1058.1	6½	1-in. plain round...........	0.98	1056.1, 1057.1	1-1.94-3.29	62	2140
	1058.2	6½	1-in. plain round...........	0.98	......	1-1.96-3.27	66	2730
	1058.3	6½	1-in. plain round...........	0.98	1052.6	1-1.93-3.32	60	2960
19	1059.1	6½	1-in. plain round...........	0.98	1061.1, 1048.1	1-2.07-3.46	60	2680
	1059.2	6½	1-in. plain round...........	0.98	......	1-1.99-3.32	66	2600
	1059.3	6½	1-in. plain round...........	0.98	1062.3	1-1.92-3.31	67	2600
20	1060.1	6½	1-in. plain round...........	0.98	1059.1, 1048.1	1-2.07-3.46	60	2680
	1060.2	6½	1-in. plain round...........	0.98	1055.5	1-2.01-3.23	64	3140
	1060.3	6½	1-in. plain round...........	0.98	1063.3, 1064.3	1-1.98-3.30	63	3250
21	1051.1	5½	1-in. plain round...........	0.98	1052.1	1-1.95-3.34	70	2120
	1051.2	5½	1-in. plain round...........	0.98	......	1-1.94-3.26	66	2800
	1051.3	5½	1-in. plain round...........	0.98	1053.3	1-1.98-3.28	68	2760
22	1053.1	7½	1-in. plain round...........	0.98	1050.4	1-1.95-3.09	60	2170
	1053.2	7½	1-in. plain round...........	0.98	......	1-1.98-3.15	62	2200
	1053.3	7½	1-in. plain round...........	0.98	1051.3	1-1.98-3.29	..	....
23	1054.1	8½	1-in. plain round...........	0.98	1046.1	1-1.93-3.26	62	2580
	1054.2	8½	1-in. plain round...........	0.98	......	1-1.96-3.28	65	2800
	1054.3	8½	1-in. plain round...........	0.98	1061.6	1-1 98-3.30	63	2870

* The average compressive strength of 36 6-in. cubes of hand-mixed concrete was 2200 lb. per sq. in.; of 93 cubes of machine-mixed concrete, 2800 lb. per sq. in.

(Table 31 continued on page 154)

TABLE 32.

Tests of Reinforced Concrete Beams—1912 Series.

All beams had 3 in. overhang at each end.
In computing unit stresses the weight of the beam was considered.
Loads are given in pounds; stresses are given in pounds per square inch.

Group	Beam No.	Test Span feet	Distance between Loads feet	Age at Test days	Load at First Outer Crack	At First Slip of End of Bar		At Maximum Load				Maximum Bond Resistance in Pull-out Tests	Failure of Beam
						Applied Load	Computed Bond Stress	Applied Load	Tensile Stress in Steel	Vertical Shearing Stress	Computed Bond Stress		
14	1052.1	6	2	67	8 000	8 000	154	19 940	36 800	149	383	356	Bond at S. end
	1052.2	6	2	59	11 000	11 000	211	18 000	33 200	136	347	405	Bond at N. end
	1052.3	6	2	64	6 000	16 000	307	20 000	36 800	150	385	......	Tension in steel
	Av.	......	......	63	8 300	11 700	224	19 300	35 600	145	372	395	
15	1056.1	6	2	65	14 000	13 000	250	15 750	29 200	119	305	454	Bond at N. end
	1056.2	6	2	65	6 000	12 500	240	19 700	36 300	149	379	392	Bond and tension in steel
	1056.3	6	2	65	10 000	13 500	260	21 000	38 600	158	403	443	Bond at N. end
	Av.	......	......	65	10 000	13 000	250	18 800	34 700	142	362	430	
16	1052.4	6	2	61	14 000	18 000	347	20 600	37 900	155	395	443	Bond at N. end
	1052.5	6	2	63	10 000	11 500	220	18 500	34 100	139	356	415	Bond at N. end
	1052.6	6	2	65	10 000	14 000	269	18 800	34 700	142	383	381	Bond at S. end
	Av.	......	......	63	11 300	14 500	279	19 300	35 600	145	372	413	
17	1057.1	6	2½	68	8 000	12 000	231	19 500	31 400	147	375	323	Bond at N. end
	1057.2	6	2½	64	8 000	13 000	250	19 100	30 800	144	368	......	Bond at S. end
	1057.3	6	2½	63	8 000	13 000	250	25 000	40 000	187	478	322	Tension in steel
	Av.	......	......	65	8 000	12 700	244	21 200	34 100	166	407	322	
18	1058.1	6	3	68	8 000	14 000	272	18 900	26 100	142	364	454	Bond at N. end
	1058.2	6	3	63	6 000	10 000	198	14 000	19 500	106	272	252	Bond at both ends
	1058.3	6	3	67	.....	13 000	254	18 600	25 700	140	359	381	Bond at N. end
	Av.	......	......	66	7 000	12 300	241	17 200	23 800	129	332	363	
19	1059.1	6	3½	64	26 000	12 000	235	33 750	38 400	251	642	591	Bond at N. end
	1059.2	6	3½	59	......	10 000	198	17 700	20 400	134	341	......	Bond at S. end
	1059.3	6	3½	62	14 000	12 000	235	22 000	25 200	165	421	416	Bond at N. end
	Av.	......	......	62	20 000	11 300	223	24 400	28 000	183	468	504	
20	1060.1	6	4	70	21 000	16 000	309	32 000	29 100	238	608	591	Bond at S. end
	1060.2	6	4	62	21 000	18 000	347	24 700	22 600	185	472	599	Bond at S. end
	1060.3	6	4	61	......	17 000	329	30 000	27 400	224	573	579	Bond at N. end
	Av.	......	......	64	21 000	17 000	328	28 900	26 400	215	551	590	
21	1051.1	5	1⅔	68	8 000	16 000	290	16 800	25 800	128	324	386	Bond at S. end
	1051.2	5	1⅔	60	6 000	13 000	252	20 000	30 600	151	383	342	Bond at S. end
	1051.3	5	1⅔	63	8 000	15 000	290	20 100	30 800	152	385	480	Bond at N. end
	Av.	......	......	64	7 300	13 700	277	19 000	29 100	144	364	403	
22	1053.1	7	2⅓	62	8 000	(No re	adings)	17 100	37 000	130	331	366	Tension in steel
	1053.2	7	2⅓	63	8 000	12 000	236	16 600	36 000	126	322	400	Bond and tension in steel
	1053.3	7	2⅓	63	8 000	16 000	310	18 400	39 800	139	356	......	Tension in steel
	Av.	......	......	63	8 000	......	......	17 400	37 600	132	336	383	
23	1054.1	8	2⅔	60	6 000	10 000	210	16 000	40 000	121	312	459	Tension in steel
	1054.2	8	2⅔	63	5 000	12 000	227	15 100	37 800	114	296	525	Tension in steel
	1054.3	8	2⅔	60	8 000	13 000	256	15 400	38 500	117	301	596	Tension in steel
	Av.	......	......	61	6 300	12 000	231	15 500	38 600	117	303	527	

(Table 32 continued on page 155.)

TABLE 31—Continued from page 152.

Data of Reinforced Concrete Beams—1912 Series.

Group	Beam No.	Length feet	Longitudinal Reinforcement: Size and Kind of Bar	Longitudinal Reinforcement: Per cent	Beam from same Batch	Mixture by Weight	Compression Tests of 6-in. Cubes*: Age days	Compression Tests of 6-in. Cubes*: Average of 3 Tests lb. per sq. in.
24	1055.1	10½	1-in. plain round	0.98	1052.4	1-2.07-3.48	61	2065
	1055.2	10½	1-in. plain round	0.98	......	1-1.99-3.28	..	....
	1055.3	10½	1-in. plain round	0.98	......	1-1.98-3.37	..	....
25	1055.4	10½	1-in. plain round	0.98	1048.4	1-2.03-3.28	61	1940
	1055.5	10½	1-in. plain round	0.98	1060.2	1-2.05-3.13	..	....
	1055.6	10½	1-in. plain round	0.98	......	1-1.97-3.27	..	....
26	1055.7	10½	1-in. plain round	0.98	1050.1	1-2.01-3.32	60	2220
	1055.8	10½	1-in. plain round	0.98	......	1-2.05-3.44	65	2980
	1055.9	10½	1-in. plain round	0.98	......	1-1.99-3.31	67	2870
27	1050.4	6½	4 ⅝-in. plain rounds	1.53	1053.1	1-1.95-3.09	60	2170
	1050.5	6½	4 ⅝-in. plain rounds	1.53	......	1-2.02-3.14	62	2700
	1050.6	6½	4 ⅝-in. plain rounds	1.53	1061.3	1-1.95-3.32	60	2390
28	1050.1	6½	3 ¾-in. plain rounds	1.66	1055.7	1-2.01-3.32	60	2220
	1050.2	6½	3 ¾-in. plain rounds	1.66	......	1-2.02-3.29	66	3290
	1050.3	6½	3 ¾-in. plain rounds	1.66	1047.3	1-1.95-3.36	..	....
29	1046.1	6½	1-in. square bar (Side horizontal)	1.25	1054.1	1-1.93-3.26	62	2580
	1046.2	6½	1-in. square bar (Side horizontal)	1.25	......	1-1.91-3.20	68	3790
	1046.3	6½	1-in. square bar (Side horizontal)	1.25	1048.3	1-1.93-3.25	59	2800
30	1046.4	6½	1-in. square bar (Placed on edge)	1.25	1047.1	1-1.96-3.29	60	2190
	1046.5	6½	1-in. square bar (Placed on edge)	1.25	......	1-1.96-3.35	68	1890
	1046.6	6½	1-in. square bar (Placed on edge)	1.25	1048.6	1-1.98-3.39	64	2080
31	1047.1	6½	1-in. twisted square bar (1 twist per lineal ft.)	1.25	1046.4	1-1.96-3.29	60	2190
	1047.2	6½	1-in. twisted square bar (1 twist per lineal ft.)	1.25	1056.3	1-1.98-3.34	71	2980
	1047.3	6½	1-in. twisted square bar (1 twist per lineal ft.)	1.25	1050.3	1-1.95-3.36	59	2670
32	1048.1	6½	1⅛-in. corrugated round	1.24	{1059.1, 1060.1}	1-2.07-3.46	60	2680
	1048.2	6½	1⅛-in. corrugated round	1.24	......	1-1.96-3.24	61	3150
	1048.3	6½	1⅛-in. corrugated round	1.24	1046.3	1-1.91-3.30	..	....
33	1048.4	6½	1⅛-in. corrugated round	1.24	1055.4	1-2.03-3.28	61	1940
	1048.5	6½	1⅛-in. corrugated round	1.24	......	1-2.05-3.19	65	3260
	1048.6	6½	1⅛-in. corrugated round	1.24	1046.6	1-1.98-3.34	..	....
34	1049.1	10½	1⅛-in. corrugated round	1.24	......	1-1.97-3.28	63	2420
	1049.2	10½	1⅛-in. corrugated round	1.24	......	1-2.01-3.19	62	2440
	1049.3	10½	1⅛-in. corrugated round	1.24	......	1-1.95-3.32	..	....

* The average compressive strength of 36 6-in. cubes of hand-mixed concrete was 2200 lb. per sq. in.; of 93 cubes of machine-mixed concrete, 2800 lb. per sq. in.

TABLE 32—CONTINUED FROM PAGE 153.
TESTS OF REINFORCED CONCRETE BEAMS—1912 SERIES.

Group	Beam No.	Test Span feet	Distance between Loads feet	Age at Test days	Load at First Outer Crack	At First Slip of End of Bar		At Maximum Load				Maximum Bond Resistance in Pull-out Tests	Failure of Beam
						Applied Load	Computed Bond Stress	Applied Load	Tensile Stress in Steel	Vertical Shearing Stress	Computed Bond Stress		
24	1055.1	10	3⅓	64	4 500	(No end slip)		12 300	39 300	94	242	443	Tension in steel
	1055.2	10	3⅓	60	4 000	12 000	240	12 300	39 300	94	246	...	Tension in steel
	1055.3	10	3⅓	2 yr.	4 000	10 400	205	11 100	34 300	86	220	560†	Tension in steel
	Av.	......	......	......	4 000	11 200	222	11 900	37 600	91	236	501	
25	1055.4	10	3⅓	64	4 000	10 800	218	10 800	34 800	83	218	459	Tension in steel
	1055.5	10	3⅓	65	4 000	9 500	190	9 900	32 200	76	201	599	Tension in steel
	1055.6‡	10	3⅓	2 yr.	4 000	10 400	215	12 100	38 700	92	236	497†	Tension in steel
	Av.	......	......	......	4 000	10 800	208	10 900	35 200	84	218	518	
26	1055.7	10	3⅓	62	4 000	12 100	242	12 100	38 700	92	242	562	Tension in steel
	1055.8*	10	6	93	4 000	10 000	203	12 800*	24 300	97	255	415	Bond at S. end
	1055.9°	10	6	85	4 000	12 000	240	16 000°	30 200	121	315	349	Bond at S. end
27	1050.4	6	2	60	10 000	24 000	195	33 700	40 300	259	269	405	Tension in steel
	1050.5	6	2	62	12 000	19 000	156	34 000	40 700	261	271	591	Tension and bond
	1050.6	6	2	60	8 000	20 000	164	27 900	33 500	215	225	503	Bond at N. end
	Av.	......	......	61	10 000	21 000	172	31 900	38 200	245	255	500	
28	1050.1	6	2	61	12 000	24 000	217	34 500	38 600	265	308	524	Bond at S. end
	1050.2	6	2	62	12 000	20 000	183	26 000	29 200	201	235	519	Bond at N. end
	1050.3	6	2	57	10 000	19 000	174	31 200	34 900	241	278	642	Bond at S. end
	Av.	......	......	60	11 300	21 000	191	30 600	34 200	235	274	562	
29	1046.1	6	2	62	8 000	11 000	174	19 000	27 800	146	293	336	Bond at S. end
	1046.2	6	2	62	10 000	11 000	174	19 300	28 200	148	298	287	Bond at S. end
	1046.3	6	2	57	10 000	14 000	219	20 500	30 000	157	316	465	Bond at S. end
	Av.	......	......	60	9 300	12 000	189	19 600	28 700	150	302	363	
30	1046.4	6	2	61	6 000	12 000	189	20 000	29 200	154	308	340	Bond at S. end
	1046.5	6	2	62	8 000	11 000	177	12 000	17 800	94	188	275	Bond at N. end
	1046.6	6	2	64	10 000	13 000	204	16 700	24 500	129	263	325	Bond at N. end
	Av.	......	......	62	8 000	12 000	190	16 200	23 800	129	253	313	
31	1047.1	6	2	62	11 000	15 000	237	21 800	31 800	167	335	447	Bond at N. end
	1047.2	6	2	65	6 000	15 000	233	23 400	34 100	179	359	510	Bond at N. end
	1047.3	6	2	60	6 000	12 500	196	20 600	30 100	158	317	443	Bond at N. end
	Av.	......	......	62	7 700	14 200	222	21 900	32 000	168	337	467	
32	1048.1	6	2	70	13 000	15 000	258	31 550	48 000	239	541	781	Bond at N. end
	1048.2	6	2	59	8 000	15 000	258	27 600	40 300	209	475	652	Bond at N. end
	1048.3	6	2	60	8 000	18 000	310	28 300	41 300	215	486	696	Bond at S. end
	Av.	......	......	63	9 700	16 000	275	29 100	41 900	231	501	710	
33	1048.4	6	2	62	8 000	12 000	206	28 000	40 800	210	482	721	Bond at S. end
	1048.5	6	2	63	8 000	14 000	240	27 700	40 500	209	477	706	Bond at N. end
	1048.6	6	2	64	8 000	17 000	292	25 000	36 600	191	431	614	Bond at N. end
	Av.	......	......	63	8 000	14 300	246	26 900	39 300	203	463	680	
34	1049.1	10	3⅓	61	6 000	18 000	310	21 000	52 500	160	369	587	Tension in steel
	1049.2	10	3⅓	63	8 000	15 000	258	21 100	52 700	161	371	521	Tension in steel
	1049.3‡	10	3⅓	400	......	16 000	275	23 200	58 300	175	400	619	Tension in steel

* A load of 10 000 lb. (which caused a slip of 0.0002 in. at S. end), was maintained for 32 days; the load was then gradually increased until the bar pulled out on the 60th day at 12 800 lb. See Art 90.

° A load of 16 000 lb. (which caused a slip of 0.0002 in. at S. end), was maintained till the bar pulled out. See Art 90.

† Tested at about 80 days.

‡ **Each load was released before a higher load was applied. See Fig. 64 and 67.**

TABLE 33.

Comparison of Bond Resistance in Beams and Pull-out Tests—1912 Series.

For data concerning the span and the position of the loads in the beam tests, see Tables 31 and 32.
The measurements of slip of bar in the beam tests refer to the end showing the greater slip.
The bond stresses given for the pull-out specimens are the average of three tests on bars embedded 8 in.
Stresses are given in pounds per square inch.

Group	Beam No.	Size and Kind of Bar	BEAM TESTS: Age at Test days	Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	Computed Bond Stress at Maximum Load	PULL-OUT TESTS: Age at Test days	Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	Maximum Bond Resistance
14	1052.1	1-in. plain round.....	67	154	216	291	349	...	383	67	211	300	331	361	375	386
	1052.2	1-in. plain round.....	59	211	300	328	...	...	347	66	161	316	363	382	400	405
	1052.3	1-in. plain round.....	64	307	338	385	...	...	385	..	...	...	...	...	...	...
	Average	....	63	224	285	335	...	...	372	66	186	308	349	371	387	395
15	1056.1	1-in. plain round.....	65	250	291	300	...	...	305	66	159	332	405	427	447	454
	1056.2	1-in. plain round.....	65	240	298	314	345	367	379	69	182	312	354	369	388	392
	1056.3	1-in. plain round.....	65	260	338	403	...	...	403	64	128	266	367	388	422	443
	Average	....	65	250	309	339	...	...	362	66	156	303	375	395	419	430
16	1052.4	1-in. plain round.....	61	347	371	384	...	...	395	64	211	344	397	417	441	443
	1052.5	1-in. plain round.....	63	220	328	356	...	...	356	71	149	307	347	376	405	415
	1052.6	1-in. plain round.....	65	269	329	340	352	362	363	71	141	308	348	360	373	381
	Average	....	63	279	343	360	...	...	371	69	167	320	363	384	406	413
17	1057.1	1-in. plain round.....	68	231	309	353	367	372	375	64	88	239	271	287	307	323
	1057.2	1-in. plain round.....	64	250	317	347	362	...	368	..	...	...	...	...	...	...
	1057.3	1-in. plain round.....	63	250	376	478	...	...	478	64	109	240	275	288	308	322
	Average	....	65	244	334	393	...	...	407	64	99	239	273	287	307	322
18	1058.1	1-in. plain round.....	68	272	314	331	347	...	364	66	159	332	405	427	447	454
	1058.2	1-in. plain round.....	63	198	208	222	242	261	272	68	119	224	241	249	253	254
	1058.3	1-in. plain round.....	67	254	291	310	331	349	359	71	141	308	348	360	373	381
	Average	....	66	241	271	288	307	...	332	68	140	288	331	345	358	363
19	1059.1	1-in. plain round.....	64	235	281	384	477	627	642	64	170	421	525	564	586	591
	1059.2	1-in. plain round.....	59	198	235	272	304	...	341	..	...	...	...	...	...	...
	1059.3	1-in. plain round.....	62	235	309	384	421	...	421	64	151	306	362	396	410	416
	Average	....	62	223	275	347	401	...	468	64	161	364	444	480	498	504

TABLE 33—Continued.

Group	Beam No.	Size and Kind of Bar	Beam Tests: Age at Test days	Beam Tests: Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	Beam Tests: Computed Bond Stress at Maximum Load	Pull-out Tests: Age at Test days	Pull-out Tests: Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	Pull-out Tests: Maximum Bond Resistance
	1060.1	1-in. plain round.....	70	309	496	...	...	...	608	64	170	421	525	564	586	591
20	1060.2	1-in. plain round.....	62	347	384	415	441	460	472	64	186	408	507	566	594	599
	1060.3	1-in. plain round.....	61	329	413	488	530	...	573	64	165	385	467	511	556	579
	Average	....	64	328	431	...	...	...	551	64	174	405	500	547	579	590
	1051.1	1-in. plain round.....	68	290	300	309	311	320	324	67	211	300	331	361	375	386
21	1051.2	1-in. plain round.....	60	252	308	346	...	...	383	60	176	256	275	294	316	342
	1051.3	1-in. plain round.....	63	290	327	346	370	385	385	65	124	340	409	433	464	480
	Average	....	64	277	312	334	...	...	364	64	170	295	338	363	385	403
	1053.1	1-in. plain round.....	62	No measurements					331	59	131	250	279	305	344	366
22	1053.2	1-in. plain round.....	63	236	273	292	300	316	322	63	202	324	359	369	389	400
	1053.3	1-in. plain round.....	63	310	348	...	...	...	356	..	...	...	...	...	...	...
	Average	....	63	273	310	...	...	...	339	62	166	287	319	337	366	383
	1054.1	1-in. plain round.....	60	210	275	297	312	...	312	60	161	329	373	398	433	459
23	1054.2	1-in. plain round.....	63	227	296	...	...	...	296	65	149	335	406	450	490	525
	1054.3	1-in. plain round.....	60	256	...	...	...	...	301	64	154	415	509	561	590	596
	Average	....	61	231	...	...	...	...	303	63	155	360	429	470	504	527
	1055.1	1-in. plain round.....	64	...	...	...	...	...	242	64	211	344	397	417	441	443
24	1055.2	1-in. plain round.....	60	240	...	...	...	...	246	..	...	...	...	...	...	...
	1055.3	1-in. plain round.....	2 yr.	205		...	...		220	82	206	364	452	505	546	560
	Average	....		...	...	...	...	...	236	73	208	354	424	461	493	501
	1055.4	1-in. plain round.....	64	218	...	...	...	...	218	63	194	329	373	398	433	459
25	1055.5	1-in. plain round.....	65	190	...	...	...	...	201	64	186	408	507	566	594	599
	1055.6	1-in. plain round.....	2 yr.	208	205	...	...		236	81	144	318	406	447	485	497
	Average	....			...	...	...	...	218	69	175	352	425	470	504	518
	1055.7	1-in. plain round.....	62	242	...	...	...	...	242	62	184	339	442	527	561	562
26	1055.8*	1-in. plain round.....	93	203	203	203	203	223	255	64	172	297	348	371	394	415
	1055.9*	1-in. plain round.....	85	240	315	...	...	...	315	65	127	252	292	309	336	349
	Average	....	80	...	...	...	...	...	...	64	161	296	361	402	430	442
	1050.4	⅝-in. plain round+...	60	195	241	...	...	...	269	70	214	306	340	363	393	405
27	1050.5	⅝-in. plain round+...	62	156	203	233	256	...	271	63	300	444	529	544	578	591
	1050.6	⅝-in. plain round+...	60	164	172	182	195	213	225	61	150	376	434	471	492	503
	Average	....	61	172	205	...	...	...	255	65	221	375	435	460	488	500

* Load continued for several days. See Art. 90. + Four bars were used in each of the beams in Group 27.

(*Table 33 continued on page 158.*)

TABLE 33—Continued.

Group	Beam No.	Size and Kind of Bar	BEAM TESTS							PULL-OUT TESTS						
			Age at Test	Bond Stress at End Slip of (inches)					Computed Bond Stress at Maximum Load	Age at Test	Bond Stress at End Slip of (inches)					Maximum Bond Resistance
			days	.0002	.0005	.001	.002	.005		days	.0002	.0005	.001	.002	.005	
28	1050.1	¾-in. plain round*...	61	217	235	269	287	...	308	62	191	377	430	467	502	524
	1050.2	¾-in. plain round*...	62	183	200	227	...	...	235	67	220	403	445	472	499	519
	1050.3	¾-in. plain round*...	57	174	200	229	252	269	278	59	248	429	546	600	633	642
	Average	....	60	191	212	242	...	...	274	63	220	403	474	513	545	562
29	1046.1	1-in. plain square....	62	174	204	238	254	279	293	60	157	233	258	275	306	336
	1046.2	1-in. plain square....	62	174	219	263	280	293	298	69	122	202	224	243	257	287
	1046.3	1-in. plain square....	57	219	263	285	298	310	316	59	173	279	371	422	457	465
	Average	....	60	189	229	262	277	294	302	63	151	238	285	313	340	363
30	1046.4	1-in. plain square....	61	189	263	298	...	...	308	61	106	192	217	242	290	340
	1046.5	1-in. plain square....	62	177	174	174	...	...	188	69	131	194	212	229	256	275
	1046.6	1-in. plain square....	64	204	219	233	241	251	263	65	113	225	255	275	304	334
	Average	....	62	190	219	235	...	...	253	65	117	204	228	249	273	316
31	1047.1	1-in. twisted square..	62	237	249	293	300	330	335	69	163	248	272	303	349	447
	1047.2	1-in. twisted square..	65	233	263	293	325	345	359	71	101	266	309	336	386	443
	1047.3	1-in. twisted square..	60	196	249	282	304	310	317	59	182	325	410	446	479	443
	Average	....	62	222	254	289	310	330	337	66	149	280	330	362	405	467
32	1048.1	1⅛-in. cor. round....	70	270	347	405	439	491	541	64	170	400	531	646	717	781
	1048.2	1⅛-in. cor. round....	59	263	330	381	425	448	475	66	185	326	391	439	494	652
	1048.3	1⅛-in. cor. round....	60	313	364	406	448	480	486	66	140	380	511	604	672	696
	Average	....	63	282	347	397	437	473	501	65	168	369	478	563	628	710
33	1048.4	1⅛-in. cor. round....	62	213	288	338	374	398	482	62	200	397	514	607	694	721
	1048.5	1⅛-in. cor. round....	63	246	321	372	405	451	477	65	169	350	491	558	619	706
	1048.6	1⅛-in. cor. round....	64	297	354	392	416	421	431	65	94	289	362	397	447	614
	Average	....	63	252	321	367	398	423	463	64	155	339	456	521	587	680
34	1049.1	1⅛-in. cor. round....	61	318	364	369	...	...	369	68	140	355	445	490	537	590
	1049.2	1⅛-in. cor. round....	63	268	307	329	353	363	371	69	146	306	365	390	414	521
	1049.3	1⅛-in. cor. round....	400	275	328	370	...	...	400	79	141	365	452	518	567	619
	Average	....	..	...	...	...	...	...	...	72	142	342	421	466	506	577

* Three bars were used in each of the beams in Group 28.

84. *Bond Resistance with Twisted Square Bars.*—The beams in group 31 were reinforced with one 1-in. twisted square bar. These bars were twisted cold (one twist per lineal foot) from the same stock as was used in the beams reinforced with plain square bars. Three pull-out specimens were made for each of the beams; the blocks were not reinforced against bursting. At an end slip of 0.0005 in. the bond stresses were 254 and 266 lb. per sq. in. for the beam tests and pull-out tests, respectively. Table 36 gives a summary of the bond stresses developed in the tests with twisted square, plain square, and plain round bars in the 1912 series.

For the two stages of the tests included in the table the twisted bars give values about 20% higher than the plain squares in the beam tests and about 34% higher in the pull-out tests. The values for the twisted bars are about 12% lower than the plain rounds in the beam tests; in the pull-out tests the twisted bars are 8% lower than the plain rounds at a slip of 0.001 in. and show about the same difference at the maximum. The maximum load for the pull-out tests with the square twisted bars came at a slip of about 0.1 in. and was accompanied by the bursting of the concrete blocks while the maximum load for the plain rounds came at a slip of about 0.01 in. The bond stresses for the square twisted and the plain round bars at a slip of 0.01 in. were 407 and 408 lb. per sq. in., respectively. These values are about the same as the maximum bond stresses for the plain rounds in the 1909 pull-out tests (see Table 14).

Load-deflection and load-slip curves for these beams are given in Fig. 85. It is seen that after end slip of about 0.001 in. is developed the action of the beams with twisted bars is quite similar to that in beams with plain square bars.

Beam No. 118, series of 1909 (see Fig. 77), reinforced with one 1-in. twisted square bar acted in much the same way as the beams just discussed, except that after an end slip of 0.004 in. the bond resistance began to increase and a second maximum load about 3000 lb. higher than the first was carried. This phenomenon is similar to that observed in pull-out tests of twisted square bars as described in Art. 41.

85. *Bond Resistance with Corrugated Bars.*—Six 6-ft. beams and three 10-ft. beams were reinforced with 1⅛-in. corrugated rounds (groups 32, 33 and 34). All the 6-ft. beams gave bond failures; the 10-ft. beams failed in tension.

TABLE 34.

Summary of Bond Stresses in Beam and Pull-out Tests—1912 Series.

Stresses are given in pounds per square inch.

Group	Characteristics	No. of Tests	Age at Test days	Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	.01	Computed Bond Stress at Maximum Load
	Beam Tests; 1-in. Plain Rounds.									
14-16	6-ft. span; Loads 2 ft. apart.........	9	64	251	312	345	.....	.....	.....	369
17	6-ft. span; Loads 2½ ft. apart.........	3	65	247	334	398	.....	.....	.....	407
18	6-ft. span; Loads 3 ft. apart.........	3	66	241	277	288	307	.....	.....	332
19	6-ft. span; Loads 3½ ft. apart.........	3	62	223	275	347	401	.....	.....	468
20	6-ft. span; Loads 4 ft. apart	3	64	328	431	.....	.....	.....	.....	551
21	5-ft. span; Loads 1⅔ ft. apart.........	3	64	277	312	334	.....	.....	.....	364
22	7-ft. span; Loads 2⅓ ft. apart.........	3	63	273	310	.....	.....	.....	.....	336
23	8-ft. span; Loads 2⅔ ft. apart.........	3	62	231	.....	.....	.....	.....	.....	303
24-26	10-ft. span; Loads 3⅓ ft. apart.........	7	.....	218	.....	.....	.....	.....	.....	230
26	10-ft. span; Loads 6 ft. apart.........	2	89	222	259	.....	.....	.....	.....	285
	Pull-out Tests; 1-in. Plain Rounds.									
14-26	Lowest two from each set of three tests.°....	54	.....	144	306	362°	389	410	417	426°
	All pull-out tests.........................	81	66	158	319	377	408	434	447	448
	Highest from each set........................	27	.....	192	347	413	450	480	491	494
	Lowest from each set......................	27	.....	123	289	340	368	384	392	399
	Beam Tests; ⅝-in. Plain Rounds.									
27	All beam tests............................	3	61	172	205	235	.....	.....	.....	255
	Pull-out Tests; ⅝-in. Plain Rounds.									
27	Lowest two from each set of three tests°.....	6	.....	194	337	394°	424	455	461	467°
	All pull-out tests.........................	9	64	221	375	435	460	490	490	500
	Highest from each set	3	.....	280	452	505	531	560	561	565
	Lowest from each set......................	3	.....	175	293	345	363	400	402	415
	Beam Tests; ¾-in. Plain Rounds.									
28	All beam tests............................	3	60	186	212	242	.....	.....	.....	274
	Pull-out Tests; ¾-in. Plain Rounds.									
28	Lowest two from each set of three tests°.....	6	.....	179	390	455°	490	519	536	537°
	All pull-out tests.........................	9	63	220	403	474	513	545	558	562
	Highest from each set......................	3	.....	301	430	510	559	595	604	611
	Lowest from each set......................	3	.....	125	365	441	476	510	524	524

° Used for comparison with bond stresses in reinforced concrete beams.

TABLE 34—Continued.

Group	Characteristics	No. of Tests	Age at Test days	Bond Stress at End Slip of (inches) .0002	.0005	.001	.002	.005	.01	Computed Bond Stress at Maximum Load
	Beam Tests; 1-in. Plain Squares.									
29-30	All beam tests	6	61	190	224	248	.....	.....	.....	278
	Pull-out Tests; 1-in. Plain Squares.									
29-30	Lowest two from each set of three tests*	12	.....	115	209	241*	266	294	309	323*
	All pull-out tests	18	64	134	221	256	281	312	328	340
	Highest from each set	6	.....	171	244	285	312	367	366	372
	Lowest from each set	6	.....	104	194	220	241	266	283	298
	Beam Tests; 1-in. Twisted Squares.									
31	All beam tests	3	61	222	254	289	310	330	.....	337
	Pull-out Tests; 1-in. Twisted Squares.									
31	Lowest two from each set of three tests*	8	.....	131	266	325*	351	386	407	428*
	All pull-out tests	12	65	145	278	330	362	403	433	467
	Highest from each set	4	.....	167	311	348	407	459	493	543
	Lowest from each set	4	.....	113	252	303	325	363	382	405
	Beam Tests; 1⅛-in. Corrugated Rounds.									
32-33	6-ft. span; loads 2 ft. apart	6	63	261	334	382	418	458	465	482
34	10-ft. span; loads 3⅓ ft. apart	2	62	293	335	349	.....	.....	.....	370
	Pull-out Tests; 1⅛-in. Corrugated Rounds.									
32-34	Lowest two from each set of three tests*	18	.....	142	332	429*	490	548	571	630*
	All pull-out tests	27	67	154	353	452	516	574	595	654
	Highest from each set	9	.....	177	394	498	570	625	639	698
	Lowest from each set	9	.....	132	304	407	470	522	546	617
	Pull-out Tests; 1-in. Rounds with Standard V-shaped Threads.									
	Lowest two from each set of three tests	16	.....	181	380	470	535	592	613	677
	All pull-out tests	24	66	206	410	505	580	642	685	725
	Highest from each set	8	.....	254	473	576	670	738	757	813
	Lowest from each set	8	.....	177	351	431	488	530	551	614

* Used for comparison with bond stresses in reinforced concrete beams.

Load-deflection and load-slip curves for the 6-ft. beams are given in Fig. 86. The ends of the bar in the 6-ft. beams give a slip of 0.001 in. at a computed bond stress of 382 lb. per sq. in. Beams with plain round bars give a bond stress of 345 lb. per sq. in. at the same amount of slip. The maximum bond resistance of the 6-ft. beams was 482 lb. per sq. in. as compared with 369 lb. per sq. in. for similar beams with 1-in. plain rounds. The load at an end slip of 0.001 in. was 79% of the maximum for the beams with corrugated bars and 94% for the beams with plain round bars. The loads at first outer cracks are about

TABLE 35.

BOND RESISTANCE IN 6-FT. BEAMS REINFORCED WITH PLAIN ROUND BARS.

Each beam was reinforced with a single round bar 1 in. or 1¼ in. in diameter.
All beams were loaded at the one-third points of the span.
Stresses are given in pounds per square inch.

Series	Groups	Number of Tests	Age at Test	Bond Stress at Slip of End of Bar of			Maximum Bond Resistance	Compressive Strength of 6-in. Cubes
				.0002 in.	.0005 in.	.001 in.		
1909	....	6	100 days	202	244	265	291	1575
1911	1-5, 9	19	8 mo.	240	306	335	377	3030
1912	14-16	9	63 days	251	312	345	369	2630
Mean	....	....	....	236	295	324	356	

the same for the 6-ft. beams reinforced with corrugated bars as for other beams tested on the same span, whether plain round, plain square, or corrugated round—about 9000 lb. The load at first end slip of bar averaged 15 200 lb. for the beams with corrugated bars and 13 100 lb. for the beams with plain rounds. The average bond stress at first slip of end of bar was 261 lb. per sq. in. for the corrugated bars and 251 lb. per sq. in. for the plain rounds. It is seen that the vertical shearing stresses developed at first outer crack noted are about the same for the two forms of bar, regardless of the difference in area of bars. At the maximum load the bond resistance of the beams reinforced with corrugated bars was about 30% higher than those with plain rounds.

The beams tested on a 10-ft. span showed end slip to begin at about the same bond stress as in the 6-ft. beams. The 10-ft. beams reinforced with corrugated bars showed cracks much nearer the supports than were found in the beams with plain bars; see Figs. 59c and 63d.

86. *Effect of Span Length.*—Besides the beams tested on a 6-ft. span, a group was tested on each of the following spans—5, 7, 8, and 10 ft. All the beams were reinforced with 1-in. plain rounds and were loaded at the one-third points of the span. Load-slip curves are given in Fig. 71 and 72. See the photographs in Fig. 63 for the appearance of these beams after failure. Nearly all the beams with spans of 7, 8 and 10 ft. failed in tension and hence did not develop their maximum resistance to bond stresses. Notwithstanding this, the longer beams give data on the slip of bar at ends and at intermediate points and on the deflections and general behavior of such beams.

TABLE 36.

BOND RESISTANCE WITH TWISTED SQUARE, SQUARE, AND ROUND BARS

6-ft. beam tests from series of 1912; see Tables 31, 32, 33 and 34.
Stresses are given in pounds per square inch.

Size and Kind of Bar	Reinforced Concrete Beam Tests			Pull-out Tests+		
	Number of Tests	At End Slip of 0.001 in.	At Maximum Load	Number of Tests	At End Slip of 0.001 in.	At Maximum Load
1 in. twisted square	3	289	337	8	325	428
1 in. plain square	6	248*	278*	12	241*	323*
1 in. plain round	9	345	369	54	362	426

+ As stated in Art. 73, the bond stresses considered in comparing the pull-out tests with the beam tests are the averages obtained after rejecting the strongest specimen from each set of three tests. See Table 34.

* Beam No. 1046.5 gave abnormally low results. Omitting this test, the values for the beam tests with plain square bars are 283 and 295 lb. per sq. in., and for the pull-out tests, 265 and 355 lb. per sq. in., respectively.

The computed bond stresses at first slip at the end of the bar were as follows:—5-ft. beams, 277; 6-ft., 257; 7-ft., 273; 8-ft., 231; 10-ft., 222 lb. per sq. in. If correction is made for the added embedded length due to the 3 in. overhang of the ends of the beam the following values of bond stress at first end slip are obtained:—5-ft., 235; 6-ft., 222; 7-ft., 244; 8-ft., 209; 10-ft., 206 lb. per sq. in. The stresses developed at the maximum loads were:—5-ft. beams, 364; 6-ft., 369; 7-ft., 336; 8-ft., 303; 10-ft., 230 lb. per sq. in. The last three values, however, do not measure the maximum bond resistance, since the beams failed by tension in the longitudinal steel.

It is seen that there is not much difference in the computed bond stresses for beams of the span lengths tested, during the early stages of the tests. This indicates that the distribution of bond stress is similar in beams of these lengths during the early stages of the test. However, it should be borne in mind that these computed values for bond represent only the average bond stress and that they give no information as to the distribution of the bond stress or the actual bond stresses developed at various points. The discussion in Art. 68 and 95 indicates the distribution of bond stress in beams of this kind.

87. *Effect of Position of Loads on Beam.*—The beams in groups 17, 18, 19 and 20 (span 6 ft.) were tested in order to study the effect of the position of the loads with respect to the beam supports. The beams in groups 21, 22 and 23, which were tested by loads applied at the one-third points of spans varying from 5 ft. to 8 ft., will be included in this discussion. All these beams had the same cross-section—8 in. wide and 10 in. effective depth—and were each reinforced with a single 1-in. plain round bar. The position of the loads with respect to the supports may be expressed in terms of the ratio of the effective depth of the beam, a, to the horizontal distance from the support to the load point, b. This ratio for the beams included in the discussion varied from 1.2 to 3.2.

To make the comparison more nearly accurate, it will be desirable in the calculations to take into account the length of embedment of the bar beyond the point of support, which in all the beams was 3 in. To do this it is assumed that the full calculated tensile stress of the bar at the load point is taken off by a bond stress which is uniform in intensity from the load point to the end of the bar. The values so calculated will be less than the computed bond stresses given in Table 32.

Fig. 50 has been plotted with the average computed bond stress for each group of beams as ordinates and with the ratio b/a as abscissas. The closed circles represent the bond stresses developed at first end slip of bar; and the open circles represent the maximum bond stresses. It will be seen that the computed bond stress at beginning of end slip is nearly the same throughout the range of the tests. This confirms the conclusion stated in the preceding paragraph in the discussion of another series of tests, that during the early stages of the test the bond stress was probably distributed in a similar manner in these beams in which the loads were applied at different points on the span. The computed bond resistances at the maximum load are greater for the smaller values of the ratio b/a; except for group 19 and 20 this difference is not large.

A study of the position of the cracks in these beams shown in Fig. 60 and 61 gives no indication that the location of the cracks is productive of these differences in the maximum bond resistance developed by the loads in different positions. Added friction due to the increased bearing pressures obtained with the beams having smaller values of b/a may increase the bond resistance somewhat, but this would be expected to affect the static friction element of bond at the beginning of slip and there is no evidence of such effect. It would seem, however, that the variation must be due to the presence of other than normal beam action.

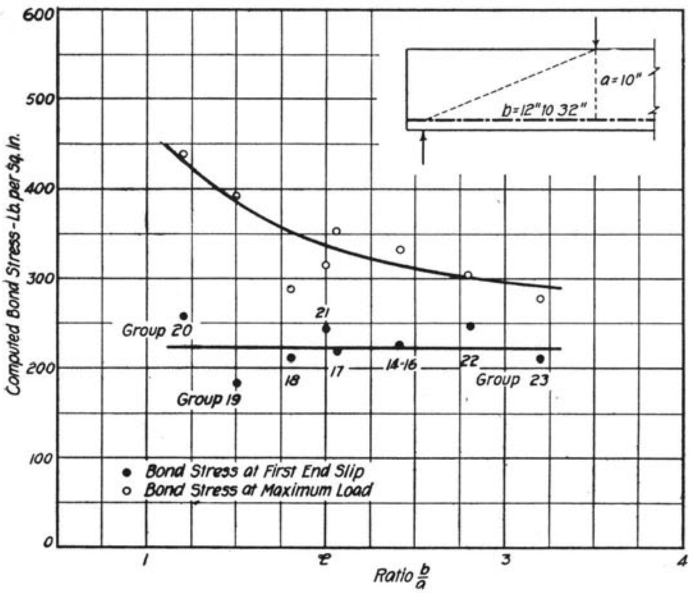


FIG. 50. EFFECT OF POSITION OF LOADS ON REINFORCED CONCRETE BEAMS.

88. *Effect of Auxiliary Reinforcement in Ends of Beams.*—In addition to the main longitudinal reinforcement, consisting of 1-in. plain round bars, the beams in Group 16 were provided with two loops of ⅜-in. round bars at each end extending from a point 3 in. inside the load points to the ends of the beam. The arrangement is shown in Fig. 2 (g). This increased the tension reinforcement outside the load points by 56%. The purpose of these tests was to discover the effect produced on the bond resistance as a result of retarding the opening of the usual outer cracks. The load-slip curves for these beams are shown

in Fig. 69, and the load-deflection curves in Fig. 81. Group 16 may be compared with Groups 14 and 15, which were the same except they did not have the auxiliary bars. The load at first crack outside the load points in Group 16 averaged 11 300 lb. as compared with 9100 lb. for Groups 14 and 15; an increase of 24%. The bond stress at first end slip of bar, computed on the area of the main bar only, is raised from 240 to 282 lb. per sq. in., an increase of 17%. The maximum bond resistance, based on the main bar only, is practically the same for each of these groups of beams.

The photograph of these beams after failure (Fig. 60b) shows a different distribution of the cracks in the beams having auxiliary bars. Generally speaking, the main cracks came inside the load points near the end of the auxiliary bars. The characteristic sloping cracks of such beams are generally absent, although it seems probable that interior cracks which did not appear on the surface may have opened to an extent that permitted the same distribution of bond stress as was found in the other beams. The most striking effect arising from use of the auxiliary bars is found in the uniformity and regularity of the slip of bar at intermediate points of the bar as shown in Fig. 69 and discussed in Art. 94.

89. *Effect of Variation in Number and Size of Reinforcing Bars.*—Four ⅝-in. plain rounds were used for longitudinal reinforcement in Group 27 and three ¾-in. rounds in Group 28. This corresponds to 1.53% and 1.66% of longitudinal steel, respectively, as compared with about 1% for the 1-in. plain rounds used in most of the beams. These beams were provided with U-shaped stirrups as shown in Fig. 2(h). The measurements of end slip were made on the two outside bars. There was a marked uniformity in the behavior of the two outside bars in nearly all the tests; generally the two instruments at the same end of the beams gave exactly the same reading; in other cases the larger value was used in plotting the load-slip curves in Fig. 84.

The relation of the bond stresses developed in the beam and pull-out tests may be seen in Table 34. In the beam tests the ⅝ and ¾-in. bars show end slip to begin at a much lower computed bond stress than for the beams with 1-in. bars, but it is worth noting that this first end slip came at loads which gave the same tensile stress in the steel at mid-span and hence presumably about the same amount of stretch of bar between load point and support. For an end slip of 0.001 in. (using the values in Groups 14 to 16 for the 1-in. bars) the average computed bond stresses are: ⅝-in. bars, 235 lb. per sq. in.; ¾-in. bars, 242; 1-in. bars, 345 lb. per sq. in. At the maximum loads the values are: 255, 274 and 369 lb. per sq. in., respectively. From this it would seem that slip is a function of amount of stretch of bar as well as of bond surface. The loads at first outer crack are about the same for each of the groups of beams. The concrete may be expected to fail in tension at about the same load, and it seems that the anti-stretch cracks form at once. The appearance of one group of beams after test is shown in Fig. 62a. By comparing the photographs of the beams in Group 27 with Group 14, it will be seen that the progress of these outer cracks may assist in explaining the difference in the bond stresses developed. For the beams reinforced with 1-in. plain rounds (Groups 14 and 15), the average distance of the outermost cracks which had appeared previous to the first slip of bar at the end where bond failure occurred, was 18 in. from the end of the beams; in Group 27, reinforced with four ⅝-in. rounds, the corresponding distance is 11 in.; in group 28, reinforced with three ¾-in. rounds, 13 in.

A consideration of the position of these outer cracks indicates that after such cracks are formed in beams of this length a large proportion of the bond stress is carried by the embedded length lying between the crack and the end of the beam, while a smaller proportion is carried by the part between the crack and the load point. This assumption makes the bond stresses of the outer embedded length more nearly the same for the three groups. It seems probable that the actual bond resistance developed in the outer embedded lengths approaches the values developed in the pull-out tests. After cracks have formed in the concrete near the load points, it may be expected that an increasae of load will produce other cracks still nearer the support due partly to anti-stretch slip. This cracking progresses step by step toward the end of the beam until the remaining unbroken embedment of the bar is no longer able to furnish necessary resistance, and the beam finally fails by the bars pulling out. The progress of the formation of cracks is very well illustrated in the beams of Groups 27 and 28. In Beam No. 1050.2 a crack opened about 3 in. outside the N. load at 8000 lb.; another appeared 5 in. farther out at 12 000 lb.; and a third at 16 000 lb. In Beam No. 1050.3 cracks appeared at the S. end at 14 000, 18 000, 29 000 and 31 000 lb.

These tests indicate that the distribution of bond stresses in beams is influenced by the relation of the dimensions of the cross-section of the beam to the diameters of the reinforcing bars.

90. *Effect of Repeated and Continued Loads on Beams.*—In testing Beam No. 84 of the 1909 series, reinforced with one 1¼-in. plain round, the load was applied progressively as in other tests, until one end of the bar had slipped about 0.0002 in. under an applied load of 15 000 lb. The load was then released to 500 lb. The residual center deflection was 0.015 in. (see Fig. 51). At first loading, 6400 lb. load was required to produce this deflection. The load was then increased to 17 000 lb., causing a slip at the north end of the bar of 0.0006 in. Upon releasing the load to 900 lb. the residual deflection was over 0.02 in. There was no recovery in the amount of the end slip of the bar upon release of the loads, although the bar had slipped an appreciable amount. The load was then reapplied up to a maximum of 20 500 lb., when the bar pulled out at the end which at first had shown the smaller slip. This phenomenon was observed in a few tests in the later series, showing that the bond resistance at the two ends was so nearly equal that failure was likely to come at either end, or at both ends at the same time. In most of the beam tests slipping was much more pronounced at one end than the other.

The lack of recovery in the slip at the end of the bar in this beam test and in the repeated load tests on pull-out specimens is significant, and seems to be characteristic of plain bars. It will be seen in the test of Beam No. 1049.3 that corrugated bars do show some recovery of slip upon release of load.

Beam No. 1055.9, reinforced with one 1-in. plain round bar, was loaded on a 10-ft. span at two points 6 ft. apart. The test progressed as usual until a load of 16 000 lb. (bond stress, 315 lb. per sq. in.) had been applied, which caused a slip of 0.0004 in. at the south end of the bar. This load was maintained until failure occurred after about 34 hours. The changes in slip of bar with the time are plotted in Fig. 52. As was seen in the pull-out tests, after slipping becomes general, there is nearly a constant difference between the total slip at the end of the bar and at point (3). The slip at (1) was probably affected by the large diagonal crack which opened at that point.

Beam No. 1039.3, reinforced with one 1-in. plain round bar, was loaded at the one-third points of a 6-ft. span. This beam was 7½ months old at the time of test. A load of 26 000 lb. caused a slip of 0.001 in. at the north end. This load was maintained constant until failure occurred after 66 hours. The end slip during the period the beam was under load is shown in Fig. 52.

Beam No. 1055.8, 10-ft. span, reinforced with one 1-in. plain round bar, was loaded at two points 6 ft. apart. The load was increased as usual until the north end of the bar showed a slip of 0.0007 in. under a load of 10 000 lb. The load was maintained at 10 000 lb. for 32 days,

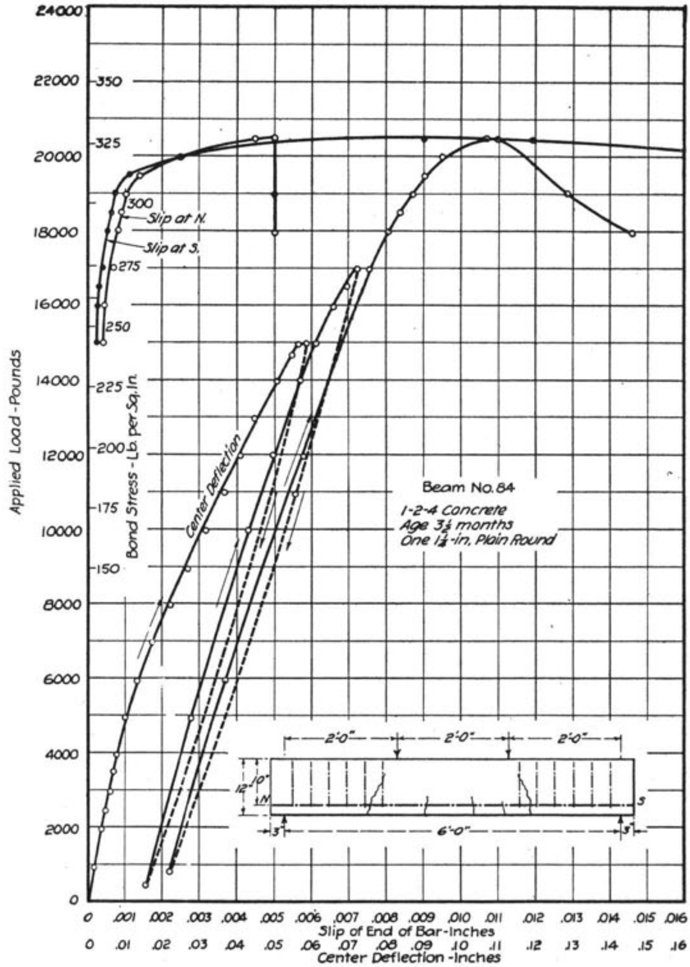


FIG. 51. LOAD-SLIP AND LOAD-DEFLECTION CURVES FOR A BEAM UNDER REPEATED LOADS.

during which frequent observations of slip of bar and deflection were taken. After 32 days the load was increased 100 lb. per day until failure occurred on the 60th day of loading under a load of 12 800 lb. The slip of bar and the center deflections are plotted in Fig. 53. Slip-

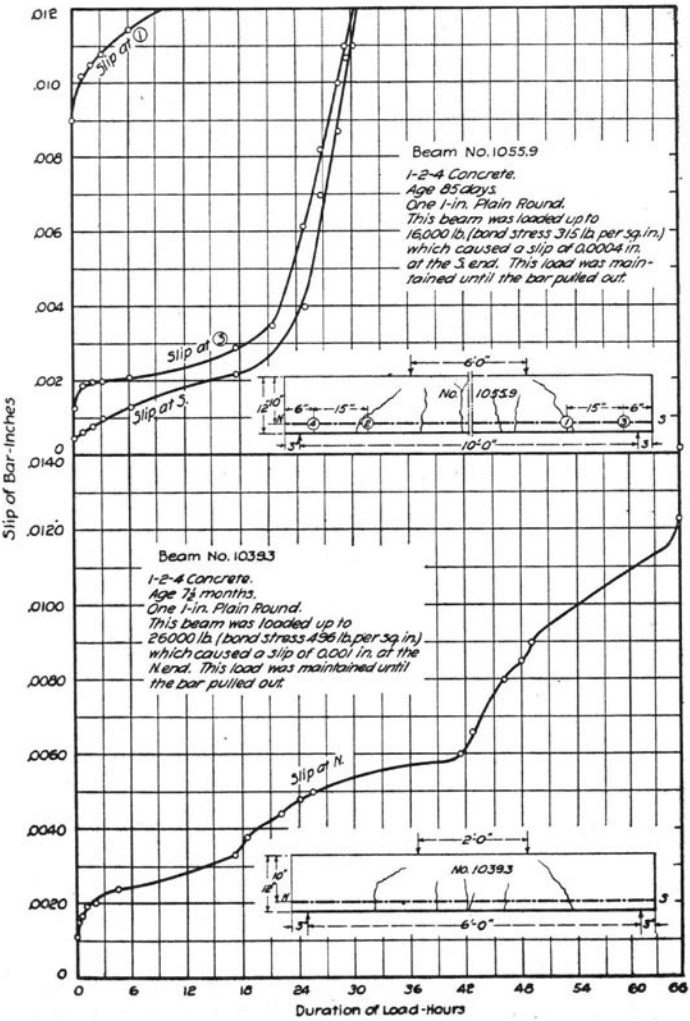


FIG. 52. SLIP OF BAR IN BEAMS UNDER CONSTANT LOADS.

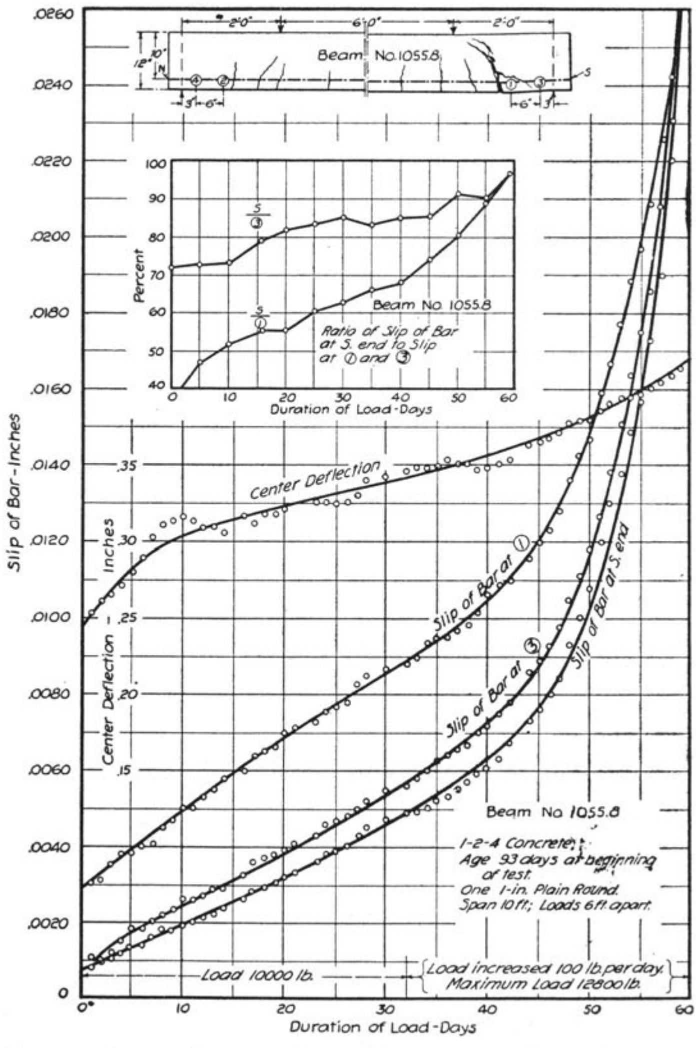


FIG. 53. SLIP OF BAR AND CENTER DEFLECTION OF BEAM NO. 1055.8.

ping continued at a nearly constant rate while the load was maintained at 10 000 lb. There was no marked change in the rate of slip until the load had been increased by about 1000 lb.

Fig. 54 shows the load-slip curves for Beam No. 1055.8. The curves have been plotted from the same origin in terms of the slip at the points where measurements were taken and the computed bond stress during the later stages of the test.

The small diagram in Fig. 53 indicates the ratio of the end slip to the slip at points 6 in. and 12 in. from the end. When the load was first applied the slip of bar at the end was 70% and 40% of the slip at points 6 and 12 in., respectively, from the end; while near failure the slip at inner points was nearly the same as at the end. The slip-of-bar curves indicate that, after slip became general, there was a nearly constant difference between the end slip and the slip at inner points

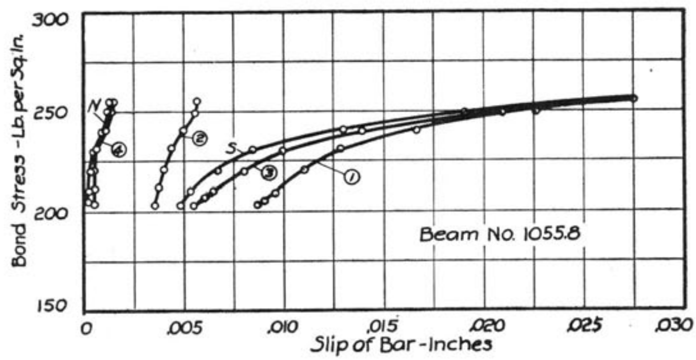


FIG. 54. LOAD-SLIP CURVES FOR BEAM No. 1055.8.

where the concrete was unbroken. It seems probable from the way slip was progressing in this test that failure would have been produced under a load of 10 000 lb., if this load had been maintained for two or three months.

The center deflection of the beam increased about 0.11 in. during the period of about 40 days in which the load was practically constant. This increase in deflection was probably due principally to the slip of the bar at the end of the beam where bond failure occurred. This slip amounted to about 0.007 in. at the south end after the beam had been under load 40 days.

The tests described above in which the load causing a very small amount of slip at the end of the bar was maintained constant indicate that with beams reinforced with plain bars the load which produces a small end slip will, if acting indefinitely, endanger the permanency of the beam.

91. *Pull-out Tests with 1912 Beam Series.*—A summary of the results of the tests on the pull-out specimens made with the 1912 beams is given in Table 34. The load-slip curves have been plotted in Fig. 55. The tests were made at the age of about 65 days. The number of specimens of each kind is indicated by figures in parentheses. In these curves the average values from all the tests have been used; while for comparison with the bond stresses developed in the corresponding beams the average of the values from the lowest two of each set of three pull-out tests should be used.

The 1-in. plain rounds averaged 448 lb. per sq. in. at the maximum; the ⅝-in. rounds about 11% higher, and the ¾-in. rounds about 25% higher. The 1-in. plain square bars gave values which are about 75% (range 69% to 78%) of those for 1-in. rounds.

In the tests with 1-in. twisted square bars end slip began at a bond stress of 278 lb. per sq. in.—about a mean between the values for the 1-in. plain rounds and the 1-in. plain squares. At an end slip of 0.02 in. the twisted bars gave a bond resistance of 448 lb. per sq. in., which is about the same as given by the plain rounds at their maximum at an end slip of 0.01 in. This is a somewhat better showing than was found for the twisted square bars in the 1909 series of pull-out tests (see Art. 41). After a slip of 0.02 in., there was very little increase in the bond resistance of the twisted square bars, which reached 467 lb. per sq. in. at an end slip of 0.1 in.; this has been considered the maximum bond resistance. The concrete blocks split at a slip of about 0.1; they were not reinforced against bursting.

The 1⅛-in. corrugated rounds gave an average bond resistance of 452 lb. per sq. in. at an end slip of 0.001 in.—about 20% higher than the 1-in. plain rounds at the same slip. At an end slip of 0.01 in., corresponding to the maximum bond resistance of the plain rounds, the corrugated bars gave 595 lb. per sq. in.—33% higher than the 1-in. plain rounds. The blocks split in all the corrugated-bar tests; splitting seemed to have begun soon after a slip of 0.01 in. was developed.

1-in. round bars, with standard threads (8 per inch), showed the highest resistance at beginning of slip; at a slip of 0.001 in. the bond resistance was 505 lb. per sq. in., as compared with 377 for the 1-in. rounds and 452 lb. per sq. in. for the 1⅛-in. corrugated rounds. At an end slip of 0.01 in. the threaded bars gave a bond resistance of 685 lb. per sq. in. These bars split the blocks soon after developing an end slip of 0.01 in.

92. *Bond Resistance in 1912 Beam Tests and Pull-out Tests.*—The summary in Table 34 shows the relation of the bond stresses for the beam and pull-out tests for the 1912 series. The dimensions of the specimen and the embedded length may be expected to affect the bond resistance corresponding to different end slips, hence it will be of interest to compare the results of the beam and pull-out tests at the same amounts of end slip. In this comparison the average values from the lowest two specimens from each set of pull-out tests was used.

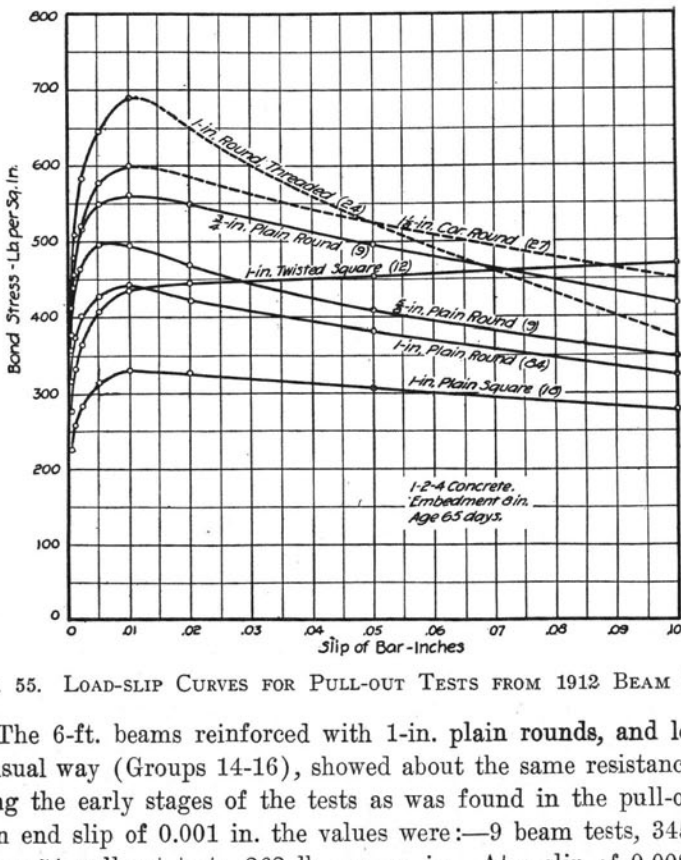


FIG. 55. LOAD-SLIP CURVES FOR PULL-OUT TESTS FROM 1912 BEAM SERIES.

The 6-ft. beams reinforced with 1-in. plain rounds, and loaded in the usual way (Groups 14-16), showed about the same resistance to slip during the early stages of the tests as was found in the pull-out tests. At an end slip of 0.001 in. the values were:—9 beam tests, 345 lb. per sq. in.; 54 pull-out tests, 362 lb. per sq. in. At a slip of 0.002 in. the pull-out tests gave a bond resistance of 389 lb. per sq. in.; the maximum bond resistance in the beams, which came at an end slip of about 0.002 in., was 369 lb. per sq. in. For the tests with 1-in. plain rounds the bond stress at an end slip of 0.001 in. was 85% of the maximum in the pull-out tests and 94% of the maximum in the beam tests.

For the 5/8-in. plain rounds at an end slip of 0.001 in. the beam tests gave a computed bond resistance of 235 lb. per sq. in.; the pull-out tests 394 lb. per sq. in. For the 3/4-in. bars the corresponding values were: beam tests, 242 lb. per sq. in.; pull-out tests, 455 lb. per sq. in. For the 5/8-in. bars the maximum computed bond stress in the beam tests was 55% of the maximum bond resistance in the pull-out tests; for the 3/4-in. bars, the corresponding value was 51%. The wide differences in the computed bond stresses in the beams reinforced with 5/8 and 3/4-in. bars and the corresponding pull-out tests are due to the changes in the distribution of the bond stresses in the beams as the test progresses, as was pointed out in Art. 68, and to the differences in the relative dimensions of the specimens.

The 1-in. plain square bars gave about the same relative values for the beam and pull-out tests as was found for the 1-in. plain rounds; at an end slip of 0.001 in. the bond stresses were: 6 beam tests, 248 lb. per sq in.; 12 pull-out tests, 241 lb. per sq. in. The bond stress at an end slip of 0.001 in. was 75% of the maximum in the pull-out tests and 89% of the maximum in the beam tests.

93. *Variation in the Results of Cube and Pull-out Tests.*—The cube and pull-out tests made of 1-2-4 concrete in the 1912 beam series offer an opportunity to study the variation which may be expected in a large number of tests made under conditions which are fairly uniform. These specimens were made from 44 batches of concrete and covered a period of about 3 months. This discussion includes 129 cube tests and 57 pull-out tests. Table 37 shows the average strength and the variation in strength for the individual cube tests and for the averages of the groups of three tests for hand-mixed and machine-mixed concrete. It will be noted that for the compression tests the mean variations of the individual tests and of the group averages are about the same for both methods of mixing. The higher strength of the machine-mixed concrete is in accordance with the usual experience, but the favorable showing as to the variation of the hand-mixed concrete is contrary to the relation usually assumed.

Table 38 shows values for the pull-out tests of 1-in. plain rounds embedded 8 in. at an end slip of 0.001 in. and for the maximum load. In this table only the machine-mixed specimens have been considered. The values for a slip of 0.001 in. and for maximum load show about the same variation. The pull-out tests show a greater mean variation from the average than the cube tests (16% and 10%, respectively); this justifies the practice of making five pull-out specimens in a set. However, it is instructive to note that the mean variations of the individual tests and of the groups for both cube tests and pull-out tests do not differ materially.

TABLE 37.

Variation in the Compressive Strength of 6-in. Concrete Cubes.

1-2-4 concrete from the 1912 beam series.
Age at test about 65 days.

Item	Hand-mixed Concrete				Machine-mixed Concrete			
	Number of Tests	Average Crushing Strength, lb. per sq. in.	Mean Variation		Number of Tests	Average Crushing Strength, lb. per sq. in.	Mean Variation	
			lb. per sq. in.	Per cent			lb. per sq. in.	Per cent
Individual tests	36	2200	204*	9.2	93	2800	294*	10.5
Average of sets of three tests	36	2200	194*	8.8	93	2800	281*	10.0

* Plus or minus.

TABLE 38.

Variation of the Values of Bond Resistance in Pull-out Tests.

Includes 57 tests with 1 in. plain round bars from the 1912 beam series.
1-2-4 machine-mixed concrete.
Embedment 8 in. Age at test, about 65 days.
Stresses are given in pounds per square inch.

Item	At End Slip of 0.001 in.					At Maximum Bond Resistance				
	Highest	Lowest	Average	Mean Variation		Highest	Lowest	Average	Mean Variation	
				lb. per sq. in.	Per cent				lb. per sq. in.	Per cent
Individual tests	546	213	371	55*	14.8	690	225	440	73*	16.6
Average of sets of three tests	509	241	371	49*	13.2	599	254	440	66*	15.0

* Plus or minus.

d. General Discussion of Reinforced Concrete Beam Tests.

94. *Slip of Bar at Internal Points in Reinforced Concrete Beams.*—In many of the beams in the 1911 and 1912 series, measurements were made to determine the amount of slip in the reinforcing bar at points other than the ends. It has been found that these load-slip relations, in view of the information derived from the pull-out tests, give valuable indications as to the bond stresses developed at different points along the length of the bar.

Load-slip curves for a few representative tests are given in Fig. 69 to 76. The curves in the figures are plotted in such a way as to indicate the amount and direction of movement of bar with respect to the adjoining concrete; they are plotted to the right or left with respect to the vertical line on the diagram which lies upon or nearest to the given point. Each horizontal division in the figures represents a slip of 0.001 in. The position of the loads, reinforcement, cracks, and other general features of the beams are indicated in the figures. The numbers within circles in the diagrams and on the photographs of the beams after failure are opposite the positions of the instruments during the test.

A survey of the load-slip curves will confirm the following observations: Slipping of the bar through the concrete was a phenomenon of all the beam tests in which observations were made. The slip was not much influenced by the form of the reinforcing bars or by variations in the points of application of the load. Slip-of-bar was quite pronounced over the middle region of the beams at loads well below those causing the appearance of the first visible cracks in the concrete; this probably indicates that tension cracks were present in the concrete some time before they became visible on the whitewashed surfaces of the beam. Since there is no bond stress due to beam action in this region of the beam, it is apparent that this is what has been termed anti-stretch slip in Art. 68. The load-slip curves for points on the beams outside the region affected by cracks are regular and show that slip increases continuously under an increasing load, or with the lapse of time under load; the curves for points within the region affected by cracks are influenced by the proximity of cracks in the concrete, and show frequent irregularities and reversals in direction. Slip-of-bar is greatest in the immediate vicinity of a crack. The indicated direction of slip in the vicinity of a crack depends upon which side of a crack the instrument was carried. The instruments on the near side of cracks somewhat removed from the middle of the beam and those approximately midway between the cracks near the middle of the beam generally show little or no slip of the bar. In general slip-of-bar is greatest on the far side of cracks near the load points. Slip-of-bar progresses from the load points or from the outermost cracks to the end of the beam at a rate nearly proportional to the increase of load. The rate of movement of the bar depends on various conditions, but it is approximately constant throughout this length after the end of the bar has slipped about 0.001 in.

It was found in these tests that the small openings in the concrete which were made in the bottom of the beams to admit the plug against which the extensometer worked, invited tension cracks, except near the ends of the beams. These cracks frequently formed directly under the plate carrying the extensometer and no doubt affected the character of some of the curves. In some cases it was impossible to tell (except as may be inferred from the form of the resulting curve) which side of the crack was carrying the instrument. It is clear that cracks cannot form in a reinforced concrete beam without more or less slip of bar, and that the instruments near cracks will indicate the greatest amount of slip at any point in their vicinity rather than the average amount over some length of bar. The curves for points near the ends, where the concrete is unbroken, are generally regular, and may be taken to represent the true load-slip relation at these points. Generally slip-of-bar was more pronounced at one end than at the other, although in some of the tests the two ends behaved nearly alike. In many of the tests it could be predicted from the observed differences in the slip measurements, some time before the completion of the test, at which end of the beam bond failure would occur.

Table 39 gives the loads corresponding to beginning of slip at the points where measurement was taken in the tests of 6-ft. beams in the 1912 series. For one-third point loading, slip of bar at the middle became appreciable at about the same load for all the beams, regardless of the kind of bar used; this load averaged about 3700 lb., corresponding to a tensile stress in the concrete of 200 lb. per sq. in., if the concrete be considered as taking the entire stress. For the same beams slip of bar began under the loads at about 4400 lb. Tension cracks in the concrete were not generally visible until the load was more than double this amount.

The load-slip curves for Beam No. 1056.2 (Fig. 69) may be considered typical of those obtained in the tests of 6-ft. beams reinforced with 1-in. plain rounds. In this test, slip was first observed in the middle portion of the beam at a load of about 4000 lb. At the middle, instrument (1), the bar is represented as moving toward the right, but the direction of movement would have been reversed had it happened that the instrument was carried on the other side of the crack. The slip at points south of the middle is greater in every instance than at the corresponding point at the north end of the beam. A general slipping of the bar occurred at the S. end at a load of about 14 000 lb.; this slip varied from about 0.0003 in. at the end to 0.005 in. at the south load point. The computed bond stress at this load was about 270 lb. per sq. in. Slipping at the north end became general at a load of about 16 000 lb. The beam failed by bond at the south end, as shown by the flattening of the curves at (3), (5), (7), and S.

In Beam No. 1052.6 (Fig. 60b and 69), in which auxiliary bars were used outside the load points, slip-of-bar in the outer thirds began at a higher load than in other similar beams without these bars. This was probably due to the auxiliary bars taking a part of the tensile stress during the early stages of the test and thus relieving the tensile stress in the main longitudinal reinforcing bar at the points where slip-of-bar was measured. These auxiliary bars had the effect of reducing the number of large cracks outside the load points (or preventing them entirely) as shown in the photograph in Fig. 60b. The prevention of large cracks seems to have had the effect of causing a more uniform distribution of the bond stress along the bar during the early stages of slip. Slip became general at both ends at a load of about 16 000 lb.; this corresponds to an average bond stress of 308 lb. per sq. in. The slip at this load varied from 0.0005 in. at the north end to 0.0012 in. 1 ft. from the supports. The pull-out tests (average of lowest two from each set) gave a bond resistance of 306 lb. per sq. in. at an end slip of 0.0005 in. The presence of the auxiliary bars had no influence on the maximum bond resistance.

The load-slip curves for the 1-in. square bars given in Fig. 74 show about the same general characteristics as those for beams with round bars. In testing Beam No. 1046.1 measurements of slip of bar were made at eleven points. The low loads at which slipping began at points (4), (6) and (8) is noteworthy; the reversal of direction in the curves for points (4) and (6) was due to the opening of cracks near these points

TABLE 39.

Applied Load at First Slip of Bar at Intermediate Points in Reinforced Concrete Beams.

All beams were tested on a 6-ft. span. The loads given in the table caused a slip of about 0.0002 in. at the points indicated.

Beam No.	Longitudinal Reinforcement	Distance between Loads feet	Maximum Applied Load pounds	Applied Load at First Slip Indicated by Instruments at Different Points. (In Units of 1000 lb.)								
				N. End	33 in. N. of Middle	24 in. N. of Middle	12 in. N. of Middle	Middle	12 in. S. of Middle	24 in. S. of Middle	33 in. S. of Middle	S. End
1056.2	1 in. plain round	2	19 700	16	14	8	4	6	6	8	15	12
1052.6	1 in. plain round	2	18 800	14	14	12	..	..	..	14	14	14
1057.2	1 in. plain round	2½	19 100	13	12	8	4	6	8	4	12	13
1058.2	1 in. plain round	3	14 000	10	10	8	4	4	4	4	11	11
1058.3	1 in. plain round	3	18 600	13	10*	6	4+	..	4+	6	8*	10
1059.2	1 in. plain round	3½	17 700	10	10	5	10	2	4	4	8	10
1060.3	1 in. plain round	4	30 000	19	21	10	10	..	10	10	17	17
1046.1	1 in. plain square	2	19 000	14	..	4	4	3	3	2	7*	11
1046.2	1 in. plain square	2	19 300	12	10	4		..	4	6	10	10
1046.4	1 in. plain square	2	20 000	11	8	8	..	4	4	6	8	13
1047.1	1 in. twisted square	2	21 800	15	14	6	6	4	6	6	13	13
1047.3	1 in. twisted square	2	20 600	12	16	4	4	..	4	6	19	17
1048.3	1⅛ in. cor. round	2	28 300	20	18	2	2	..	2	6	8	18
1048.4	1⅛ in. cor. round	2	28 000	13	15	4	4	2	2	4	..	10

+ Instruments were 18 in. from the middle of the beam.

* Instruments were 30 in. from the middle.

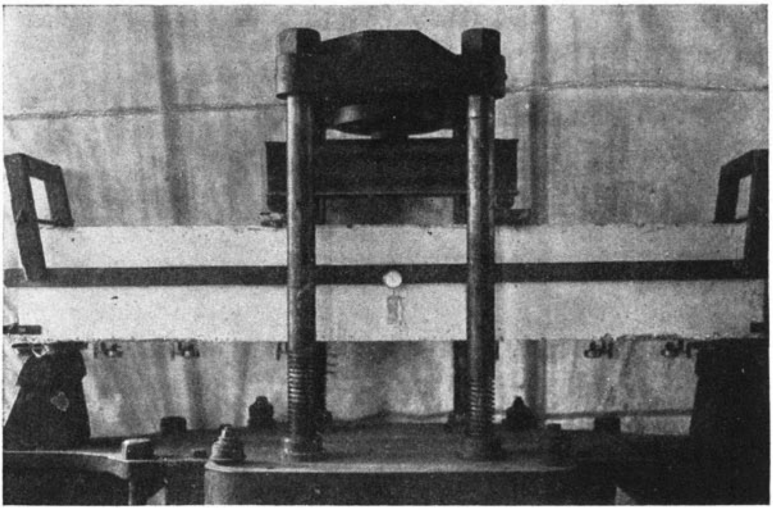
at a load of about 7000 lb. In spite of the large amount of slip at point (8), failure occurred in the beam at the opposite end. The curves for corresponding points at the opposite ends of Beam No. 1046.2 show an unusual uniformity. It will be seen by reference to Fig. 62b that cracks had formed near each of the instruments (2), (3), (4), and (5); the symmetry of the curves is due to the fact that the instruments were in each case carried by the concrete outside the crack. The curves for Beam No. 1046.4 show the bar to have been slipping in one direction throughout nearly two-thirds of its length; however, the presence of a crack at the middle makes the indicated direction of movement of the bar at this point depend upon which side of the crack the instrument happened to be carried.

Slip-of-bar measurements at intermediate points were made on two beams reinforced with 1-in. twisted square bars (see Fig. 75). The bond stresses developed were lower than those found with beams reinforced with 1-in. plain rounds. The curves for these tests exhibit about the same characteristics as in the beams with plain bars. Vertical and diagonal cracks formed during the progress of the tests with about the same frequency as in the other beams. The nearly vertical direction of the curve for instrument (2) in Beam No. 1047.1 is due to the presence of a crack at this point. The load-slip curves for the north ends of Beams No. 1047.1 and 1047.3 and for points 6 in. from the north end showed a large increase of slip at an applied load of about 15,000 lb., immediately after slip at these points became appreciable.

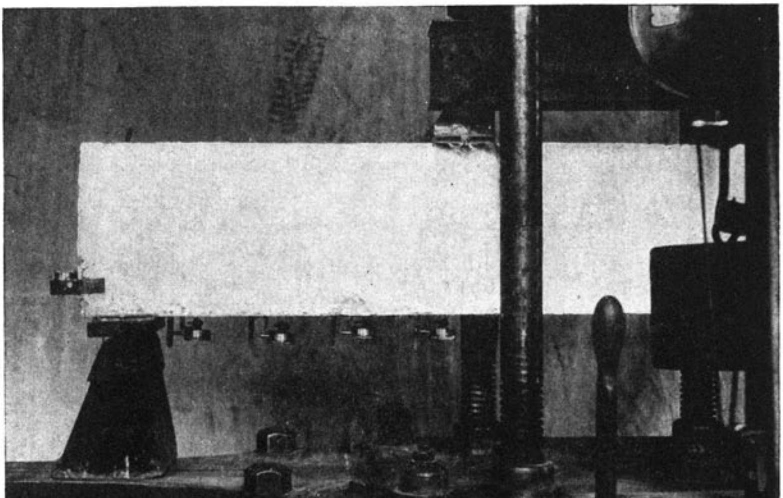
Measurements of slip of bar at intermediate points were taken on four beams in which 1⅛-in. corrugated rounds were used for longitudinal reinforcement. Two beams (1048.3 and 1048.4) were tested on a 6-ft. span and two (1049.2 and 1049.3) were tested on a 10-ft. span. Load-slip curves are given in Fig. 75 and 76. Slip began at points near the middle of the beam at approximately the same loads as in the beams reinforced with plain bars. In the outer thirds, after slip began, the corrugated bar moved at a slower rate under a somewhat higher bond stress than the plain bars. Cracks in the beams reinforced with corrugated bars occurred with about the same frequency as in the beams with plain bars. The curves for points (2), (3), (4), and (5) on Beam No. 1048.3 (see Fig. 76) illustrate the effect of cracks on the amount of movement of the bar at the various points with respect to the adjacent concrete. Instrument (2) was carried by the concrete outside the crack, hence registered a very large movement; instrument (3) was carried by the concrete inside the crack, hence showed practically no slip. The crack near instrument (4) crossed the bottom of the beam in such a way that the instrument was carried by the concrete on both sides of the crack. Instrument (5) was about 3 in. outside a crack until near the maximum load, hence indicated about the normal amount of slip. The instruments at the ends and at points (6) and (7) were undisturbed by cracks and hence more nearly indicate the relation between load and the amount of slip, which may be expected under these conditions.

The influence of span length on the slip of the reinforcing bars at internal points is shown for typical tests in Fig. 71, 72 and 73. The span varied from 5 to 10 ft.; the points of application of the load are shown in the figures. For convenience of reference the curves for Beam No. 1056.2 (6-ft. span) are repeated here to the same scale as used in the beams of other spans. It should be borne in mind that in general the 8 and 10-ft. beams failed in tension. The curves for Beam No. 1051.2 (5-ft. span) are about the same as found for the 6-ft. beams; slip became appreciable near the middle at a load of about 4000 lb. and gradually extended toward each end. The bond stresses developed in the 5-ft. beams at first end slip and at the maximum loads are about the same as for the similar beams of 6-ft. span. Slip began near the middle of the 7-ft. beams at a somewhat lower load than in the 6-ft. beams; slip near the ends of the bars began at a bond stress a little higher than in the 6-ft. beams. In the 8-ft. beams slip began near the middle at about the same load as in the 7-ft. beams. The slip at the ends of the bars did not amount to more than 0.001 in. in any case. In the 10-ft. beams loaded at the one-third points, slip of the bar became apppreciable near the middle at applied loads below 2000 lb. Slip began at points 3 in. inside the supports at about the same load as in the 6-ft. beams. At the ends of the bars slip was only beginning at the maximum load.

The 10-ft. beams loaded at two points 6 ft. apart behaved in much the same way as the 6-ft. beam of the same kind loaded at the one-third points. This is as was expected, since the relation of the dimensions of the beam (as far as bond and web stresses are concerned) were the same in both cases. These tests show that local slip of bar near the middle of the beam is found at loads which are lower than those at which tension cracks appear in the concrete; this probably indicates that cracks were present some time before they became visible, and that beginning of slip was probably coincident with the opening of the most minute tension cracks.

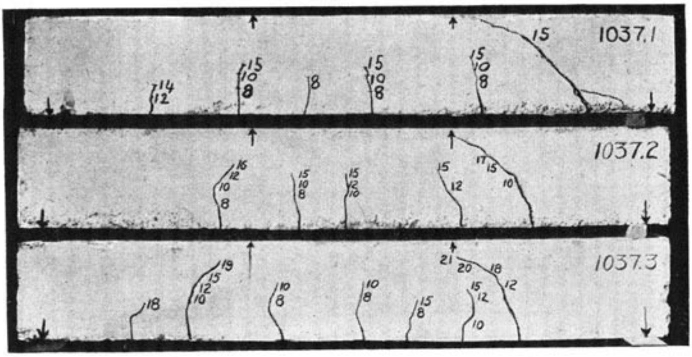


(a) Showing Instruments for Measuring Center Deflection and Slip of Bar at Intermediate Points.

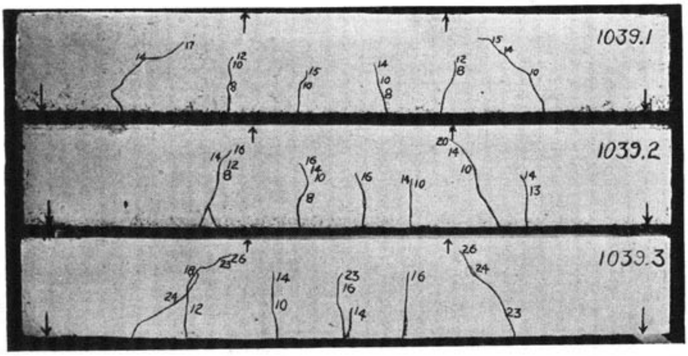


(b) Showing Instruments for Measuring Slip of Bar at End and at Intermediate Points.

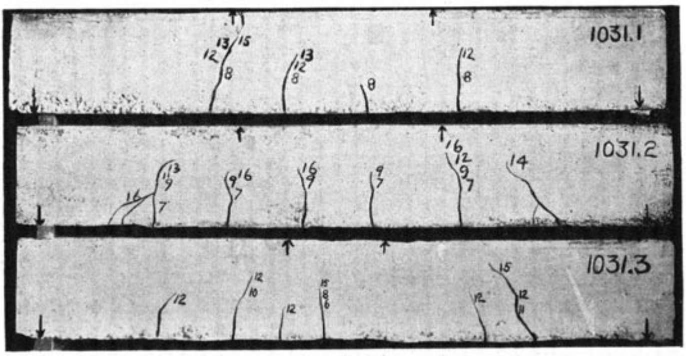
FIG. 56. REINFORCED CONCRETE BEAMS IN MACHINE READY FOR TEST.



(a) Group 1. One 1-in. Plain Round Bar; No Stirrups.

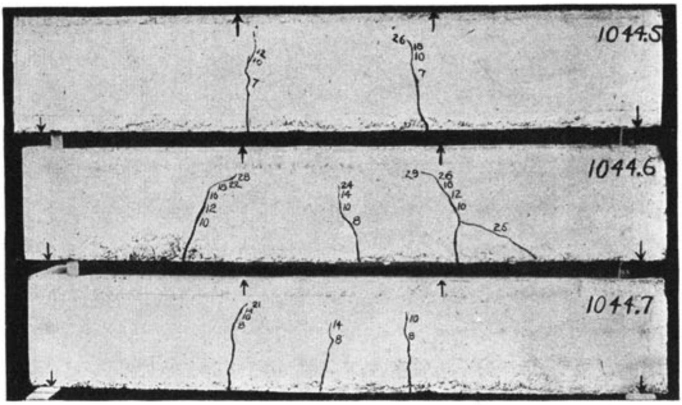


(b) Group 2. One 1-in. Plain Round Bar; ¼-in. Stirrups.

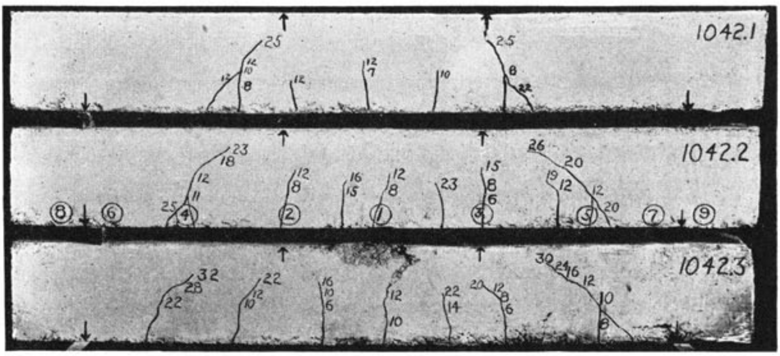


(c) Group 3. One 1-in. Plain Round Bar; ½-in. Stirrups.

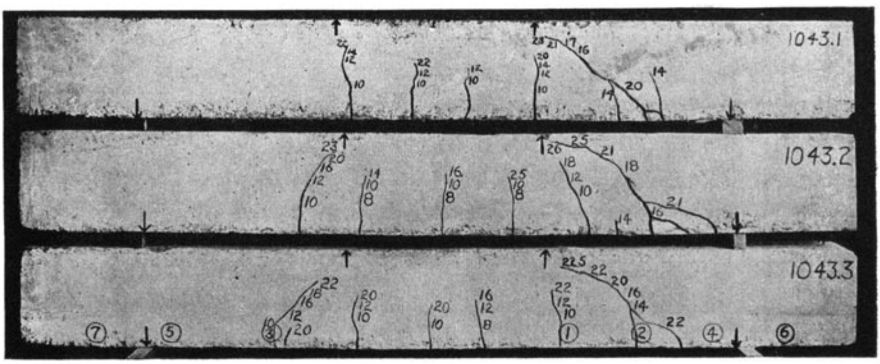
FIG. 57. REINFORCED CONCRETE BEAMS AFTER TEST—1911 SERIES.



(a) Group 6. One 1-in. Plain Round Bar; 4 in. of Concrete Below Bar; No Stirrups.

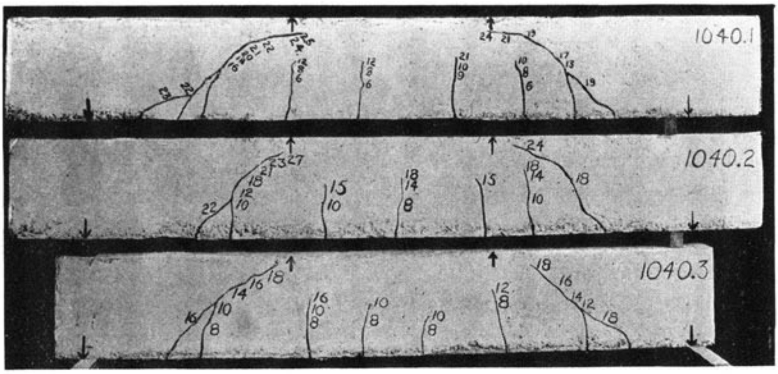


(b) Groups 7 and 13. Ends of Beams Overhanging Supports 9 in.

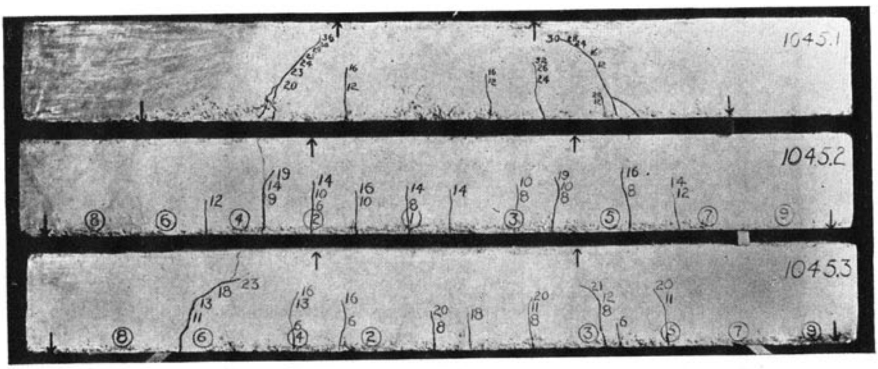


(c) Groups 8 and 10. Ends of Beams Overhanging Supports 15 in.

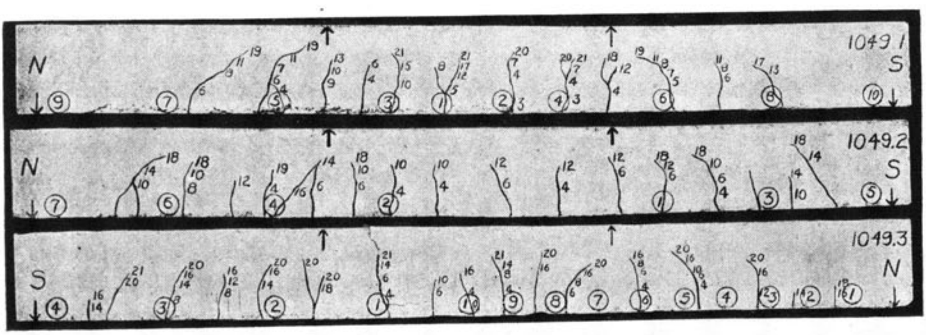
Fig. 58. Reinforced Concrete Beams after Test—1911 Series.



(a) Groups 1 and 13. Beams No. 1040.1 and 1040.2 were Each Reinforced with One 1⅛-in. Corrugated Round Bar.

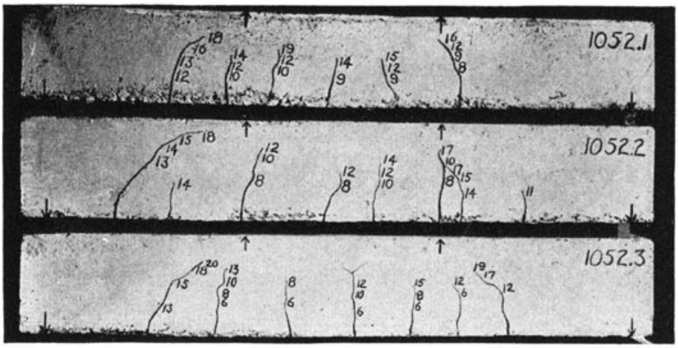


(b) Groups 10 and 11. One 1¼-in. Plain Round Bar.

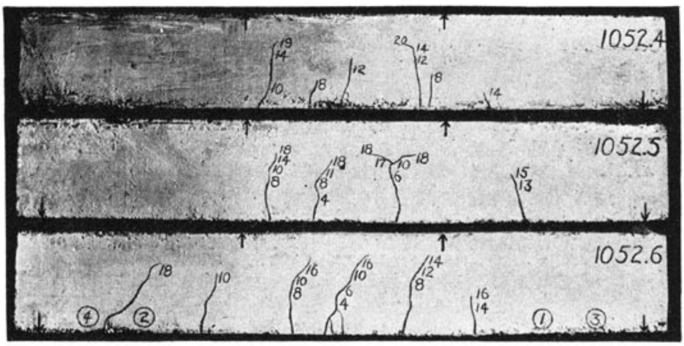


(c) Group 34. One 1⅛-in. Corrugated Round Bar; Span 10 ft.

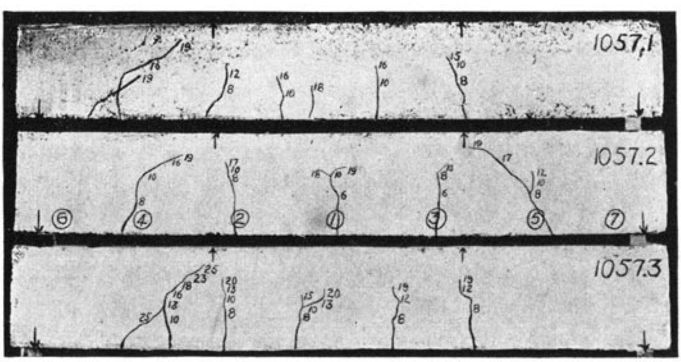
FIG. 59. REINFORCED CONCRETE BEAMS AFTER TEST.



(a) Group 14. One 1-in. Plain Round Bar.

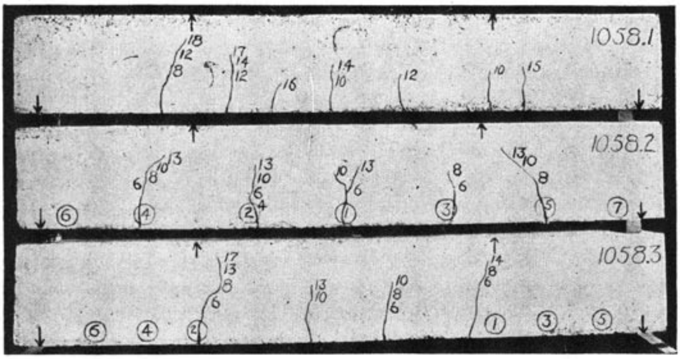


(b) Group 16. One 1-in. Plain Round Bar; Auxiliary Bars at Each End of Beam.

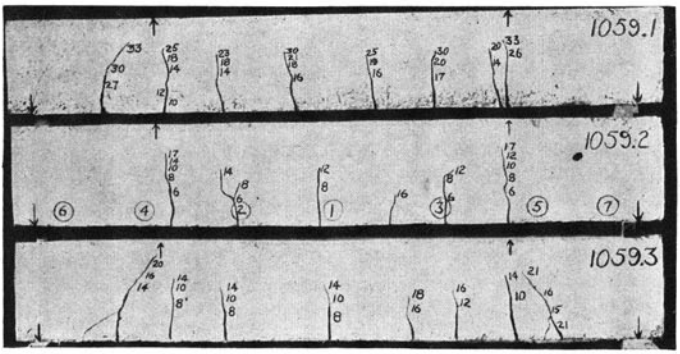


(c) Group 17. One 1-in. Plain Round Bar, Span 6 ft.; Loads $2\frac{1}{2}$ ft. Apart.

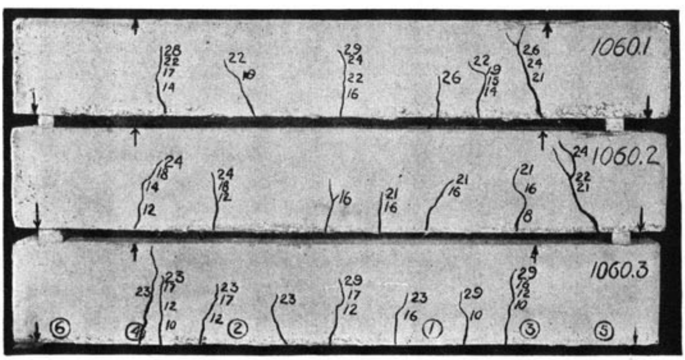
FIG. 60. REINFORCED CONCRETE BEAMS AFTER TEST—1912 SERIES.



(a) Group 18. One 1-in. Plain Round Bar, Span 6 ft.; Loads 3 ft. Apart.

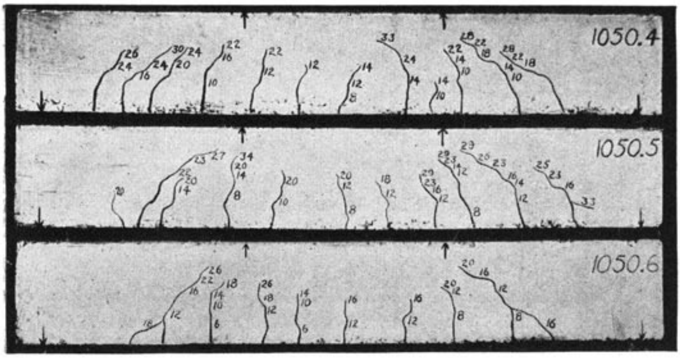


(b) Group 19. One 1-in. Plain Round Bar, Span 6 ft.; Loads 3½ ft. Apart.

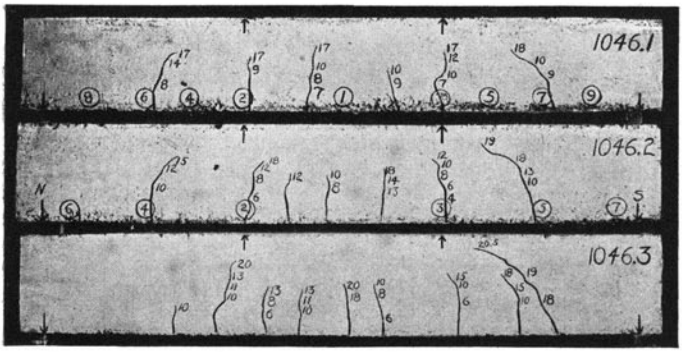


(c) Group 20. One 1-in. Plain Round Bar, Span 6 ft.; Loads 4 ft. Apart.

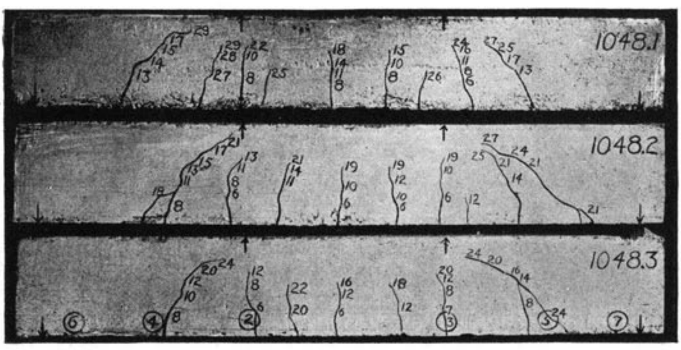
FIG. 61. REINFORCED CONCRETE BEAMS AFTER TEST—1912 SERIES.



(a) Group 27. Four ⅝-in. Plain Round Bars.

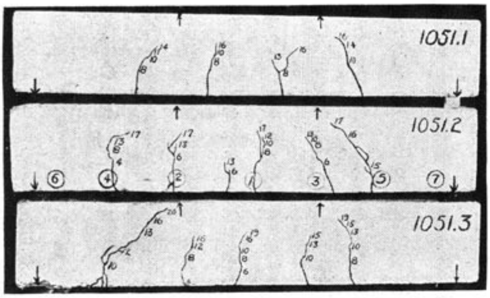


(b) Group 29. One 1-in. Plain Square Bar.

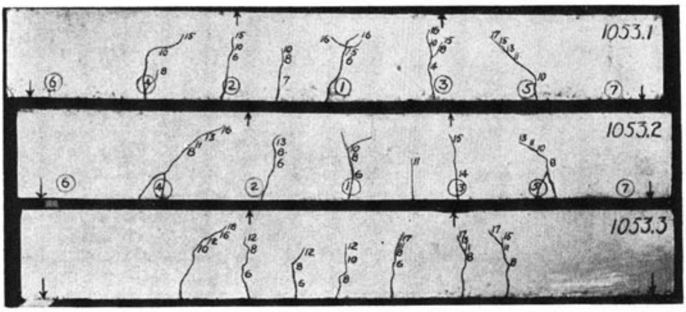


(c) Group 32. One 1⅛-in. Corrugated Round Bar.

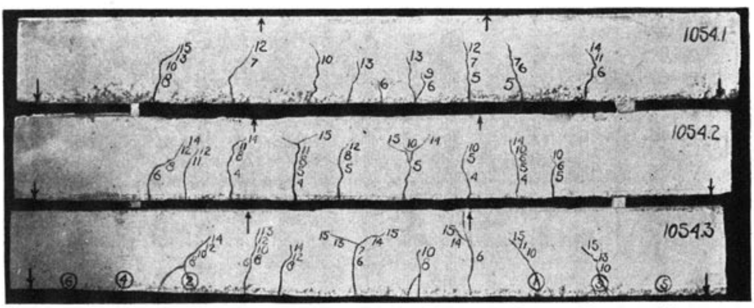
FIG. 62. REINFORCED CONCRETE BEAMS AFTER TEST—1912 SERIES.



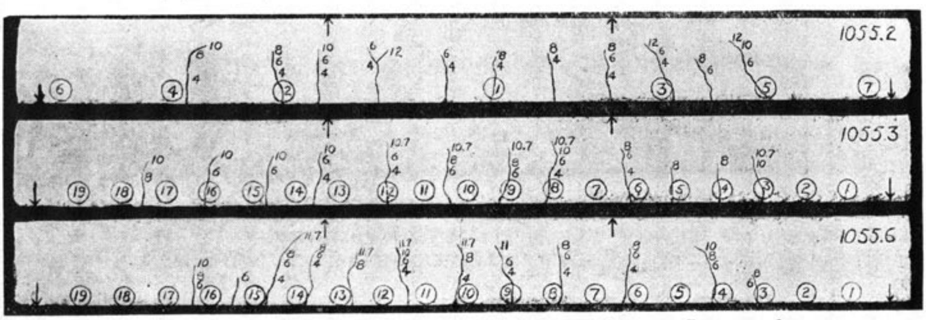
(a) Group 21. One 1-in. Plain Round Bar; Span 5 ft.



(b) Group 22. One 1-in. Plain Round Bar; Span 7 ft.



(c) Group 23. One 1-in. Plain Round Bar; Span 8 ft.



(d) Groups 24 and 25. One 1-in. Plain Round Bar; Span 10 ft.

FIG. 63. REINFORCED CONCRETE BEAMS AFTER TEST—1912 SERIES.

The curves for the groups of 6-ft. beams in which the loads were applied at varying distances apart exhibit some distinctive characteristics (see Fig. 69 and 70). These tests show with unusual distinctness the progress of slip of the bar from the middle toward the ends of the beams. There are many illustrations in this group as to the effect of cracks on the slip of the bar. The curves for point (1) in Beams No. 1056.2 and 1057.2 show the amount of slip which may be expected very close to a crack at the middle of a beam; the curves for points (1) and (2) in Beam No. 1060.3 show that little or no slip occurred at points midway between two cracks in the portion of the beam where vertical shear was absent; the curves for points (2) and (4) in Beam No. 1057.2 and for points (2) and (3) in Beam No. 1056.2 show that slip of bar may be erratic at points on the near side of a crack. Slip at points outside the loads was abnormally large on the far side of the cracks.

95. *Distribution of Tensile Stress along Reinforcing Bar.*—The usual analysis of the stresses in a reinforced concrete beam indicates that in a beam loaded as in these tests (disregarding the weight of the beam) the tensile stress in the reinforcement is uniform between the loads and decreases at a uniform rate from the load points towards the ends, becoming zero at the supports. The slip of bar measurements which were made in many of the reinforced concrete beam tests gave some indication of the bond stresses being developed as long as the amount of slip was small and showed the general variations in bond stresses, but it will be recognized that after the slip of bar has reached an amount approximating that corresponding to the maximum bond resistance, such measurements are of no further value in indicating the amount of bond stress being developed. There are indications that the amount of slip corresponding to the maximum bond resistance of plain bars was not nearly so well defined in the beams as it was in the pull-out tests. In order to learn the amount of bond stress being developed over any given length of bar in a reinforced concrete member, we must first determine the exact stress developed in the reinforcing bar at each point over this length for a given load. If we can accurately determine the variations in the steel stress the bond stress will also be known, since the bond stress developed in any length of bar represents the change in tensile stress over that length.

In the tests of three beams in the 1912 series careful measurements were made to determine the stress in the longitudinal reinforcing bar at frequent intervals throughout the span length. These tests will be discussed in detail in the following paragraphs. All of these beams were 8 by 12 in. in section, 10 in. deep to the center of the reinforcing bar; they were tested by loads applied at the one-third points of a 10-ft. span. Beams No. 1055.3 and 1055.6 were each reinforced with one 1-in. plain round bar; Beam No. 1049.3 was reinforced with one 1⅛-in. corrugated round bar. In Beam No. 1049.3 the tensile stresses were measured at 10 6-in. gauge lengths over only one-half the span length; in the other two tests the stresses were measured at 19 gauge lengths over the entire span. In all the tests the gauge lines formed a continuous series. A non-fixed strain gauge was used in determining the change in stress.* Load was applied in increments of about 2000 lb. In the test of Beam No. 1055.3 the deformations in the reinforcing bar were measured at each increment of load; in the other two tests each load was released and measurements were taken to determine the residual stresses, before applying a higher load. In Fig. 64 to 67 the distribution of bond and steel stresses are shown for different loads on the beams. In these figures the ordinates or abscissas to the curves show the amount of the stress in the reinforcing bar at any point for the loads shown, while the slope of these curves is proportional to the bond stress being developed. In Fig. 64 and 65 the curves for Beams No. 1055.3 and 1055.6 have been plotted by averaging the stresses at the corresponding gauge lines at the two ends of the beam and plotting the resulting values as the stresses for one-half the span length. This probably accounts in some measure for the greater regularity in the curves for beams reinforced with plain bars. It should be pointed out here that the values for steel stresses were determined from measurements over a 6-in. gauge length, and it is evident that the stress may vary considerably over this length of bar, especially at points where the bar has not slipped an amount corresponding to the maximum bond resistance. The stresses given on the diagrams are the averages over the entire gauge length. The plotted points indicate the location of the middles of the gauge lengths. It seems probable that a 6-in. gauge length was too long to accurately locate the points of maximum bond stress in the region affected by cracks, but it was not practicable to use a shorter gauge length. Of course, the usual errors of observation may be expected to affect measurements of this kind. The presence of tensile cracks in the concrete was another disturbing factor.

*For a detailed discussion of this strain gauge see "Tests of Reinforced Concrete Buildings Under Load," by Arthur N. Talbot and Willis A. Slater, University of Illinois Engineering Experiment Station Bulletin No. 64, 1913. Also, "Use of the Strain Gage in Testing Materials," by Willis A. Slater and Herbert F. Moore; "Proceedings of the American Society for Testing Materials," 1913.

Table 40 gives some of the significant bond stresses for these beams as computed by the usual method and as determined from the steel stress measurements. In this table and in the figures only the stresses due to the applied loads have been considered. The first column of observed stresses are generally the average stresses over a length of about 12 in. in the portion of the beam about 4 to 16 in. outside the load points. The other column shows the average observed stresses over a length of 9 to 15 in. at the ends of the beam. The photographs in Fig. 59 and 63 show the location of cracks in these beams and their growth with increase of load. The numbers inside the circles at the level of the reinforcing bars are opposite the points at which measurements of steel stress were made.

TABLE 40.

Distribution of Bond Stress in Reinforced Concrete Beams.

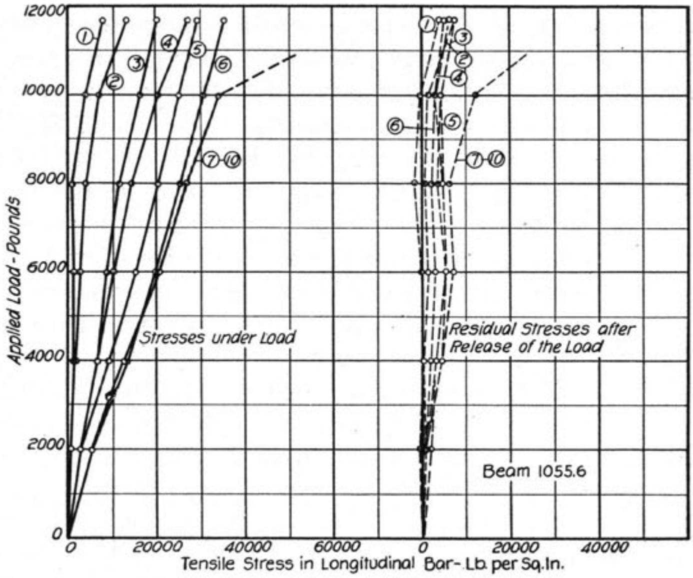
Beams 8 by 12 in. in section, 10 in. deep to center of reinforcing bar. Loaded at the one-third points of a 10-ft. span.

All beams failed by excessive tensile stress in the reinforcing bars.

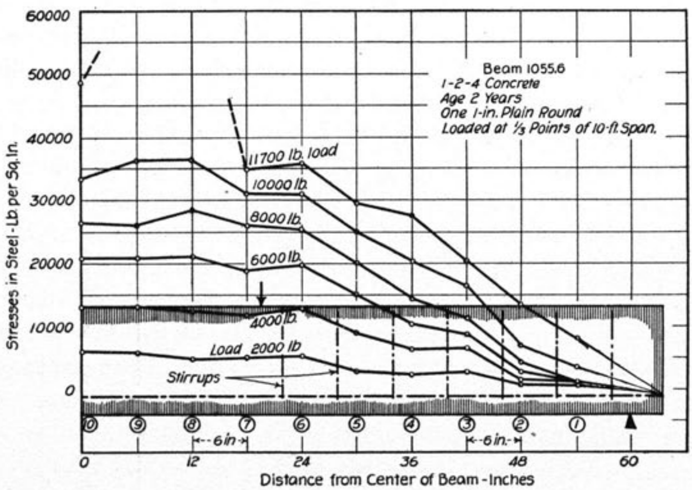
Beam No.	Size and Kind of Bar	Age at Test	Applied Load on Beam pounds	Average Computed Bond Stress lb. per sq. in.	Observed Bond Stress: Over Region just Outside of Load Points* lb. per sq. in.	Observed Bond Stress: Near Ends of Beam† lb. per sq. in.
1055.6	One 1-in. Plain Round	2 yr.	2 000	38	100	16
			4 000	76	125	34
			6 000	114	191	36
			8 000	152	226	64
			10 000	190	201	117
			11 700	222	165	238
1055.3	One 1-in. Plain Round	2 yr.	2 000	38	48	15
			4 000	76	75	54
			6 000	114	155	95
			8 000	152	141	100
			10 000	190	200	130
			10 700	203	140	156
1049.3	One 1⅛-in. Corrugated Round	13 mo.	2 000	34	80	20
			4 000	68	137	45
			6 000	102	226	95
			8 000	135	285	135
			10 000	170	250	150
			12 000	204	315	150
			14 000	236	350	225
			16 000	270	385	260
			18 000	306	400	290
			20 000	338	450	315
			21 000	355	200	360
			21 900	370	...	390

* These stresses are, in general, the average bond stresses developed over a length of about 12 in. in the portion of the beam about 4 to 16 in. outside the load points.

† The average observed stress over a length of 9 to 15 in. at the ends of the beam.



(a) Load-Stress Curves for Longitudinal Bar.



(b) Distribution of Tensile Stress in Longitudinal Bar.

FIG. 64. DIAGRAMS FROM TEST OF BEAM NO. 1055.6. ONE 1-IN. PLAIN ROUND BAR; SPAN 10 FT.

Beam No. 1055.6, reinforced with one 1-in. plain round bar, failed by tension in the steel, although slip at each end of the bar at the maximum load amounted to about 0.002 in. From measurements of steel stress in this test it is seen that there is a wide variation in the bond stresses developed at a given load along the bar through the region where beam bond stress is present. At a load of 2000 lb. the steel stress through the middle third of the beam was nearly constant, with evidence of the highest stress about 6 in. outside the load point. It is significant that the photograph of this beam, Fig. 63d, shows a crack at this point on both ends of the beam. This crack was not observed until a load of 4000 lb. had been applied, but it is evident that the measurements at 2000 lb. load indicate that stresses higher than usual were being developed at these points. At a load of 2000 lb. the average bond stress developed over the 6-in. length between the gauge lines (6) and (5) was about 100 lb. per sq. in.; a stress of about the same value was being developed between gauge lines (3) and (2), and it is significant that cracks opened at these points at low loads. It seems probable that the highest bond stress developed at a load of 2000 lb. was considerably higher than 100 lb. per sq. in., since the measurements over 6-in. gauge lengths probably did not show the most rapid changes in steel stress. Over the 15-in. length from (2) to the end of the beam the bond stress at this load was about 16 lb. per sq. in. At this load the computed bond stress was 38 lb. per sq. in. With a load of 4000 lb. the average bond stress developed over the 12-in. length from (6) to (4) was 125 lb. per sq. in.; from (3) to (2) about 200 lb. per sq. in.; from (2) to the end, 34 lb. per sq. in. The computed bond stress due to an applied load of 4000 lb. was 76 lb. per sq. in. In other words, an applied load of 4000 lb., which developed a steel stress in the middle third of about 13 000 lb. per sq. in., developed a bond stress over certain regions of the span length equivalent to 90% of the computed bond stress at the maximum load carried by the beam. A load of 6000 lb., which produced a tensile stress in the bar at the middle third of the span of about 20 000 lb. per sq. in., developed a bond stress between (6) and (5) of 191 lb. per sq. in.; at the end of the beam the stress at this load was 36 lb. per sq. in. A load of 8000 lb. produced a bond stress from (6) to (4) of 226 lb. per sq. in., and 64 lb. per sq. in. at the end; the computed bond stress at this load was 152 lb. per sq. in. With a load of 10 000 lb. on the beam the average bond stress over the length of 12 in. from (6) to (4) was 201 lb. per sq. in., or lower than was found in this region at a load of 8000 lb.; from (3) to (2) the indicated load stress was 390 lb. per sq. in., but it is possible that the points plotted for steel stress are somewhat erratic. There was a marked shifting of the stresses following a load of 10 000 lb. At the maximum applied load of 11 700 lb. the bond stress at points just outside the load had fallen still lower, while the stress near the ends of the beam was more than double what it was under a load of 10 000 lb. At the maximum load the highest bond stress was developed between points (4) and (2) and amounted to about 294 lb. per sq. in. It will be seen from Fig. 64b that the region of maximum bond stress was thrown from near the load point toward the end of the beam as the loading continued. It should be borne in mind that this beam was 2 years old at the time of test and did not fail by bond. The values in Table 40 show some of the changes which the bond stresses underwent as the load was increased. The bond stress near the load point did not show any marked increase after a load of 6000 lb., while at the end there was a continuous increase up to the maximum applied load. Still higher bond stresses could have been developed near the ends of the beam had the bar been of steel with a higher yield point. Fig. 64a shows that the residual stress in the reinforcing bar upon release of load was about proportional to the stress under load for the lower loads. After a load of 6000 lb. there is no further increase in the residual stresses. At loads near the maximum the residual stresses were nearly equal at all points except over the gauge lines nearest the ends.

Beam No. 1055.3, reinforced with one 1-in. plain round, was similar to No. 1055.6. In this test the loads were not released. Fig. 65 shows the distribution of the tensile stress in the reinforcing bar for different loads; the plotted points are the averages of the measurements at corresponding points in the two ends of the beam. This beam did not show as wide variations of bond stress as were found in the test of Beam No. 1055.6 discussed above, but many features of the tests are similar. It is noteworthy that the bond stresses developed near the ends of the beam were never more than about 75% of the computed bond stress. The bond stresses near the end are shown to be low by the fact that at the maximum load the end slip of the bar was only 0.0003 in. This beam failed by tension in the reinforcing bar. A further examination of the results of these tests on beams of similar make-up, as shown in the tables and diagrams, will indicate how much variation may be expected in the action of beams which are of the same dimensions and made of the same materials.

Beam No. 1049.3 was reinforced with one 1⅛-in. corrugated round bar of high-carbon steel. This beam was tested at the age of 13 mo. on a 10-ft. span. Measurements were made to determine the variation in stress in the reinforcing bar at 10 points along one-half the span length and to determine the amount of slip of bar at five points of the other half of the span. A complete set of observations were taken after the application of each load and another upon releasing each load. The observed values of steel stress and slip of bar are plotted in Fig. 66 and 67. It will be noted that the load-stress curves from this test show much greater irregularities than were found in the other tests. This is probably largely due to the fact that in this test the

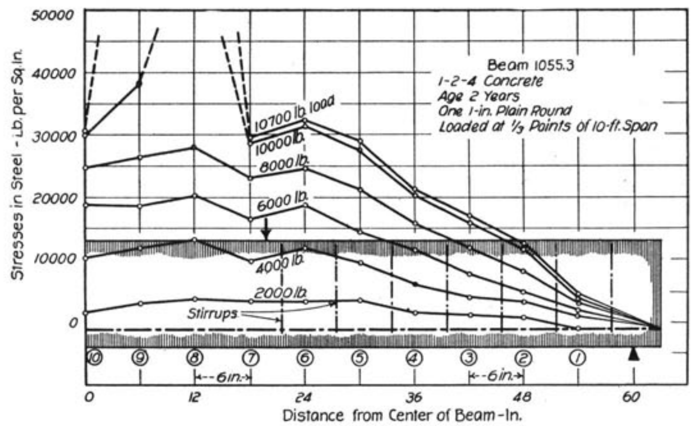
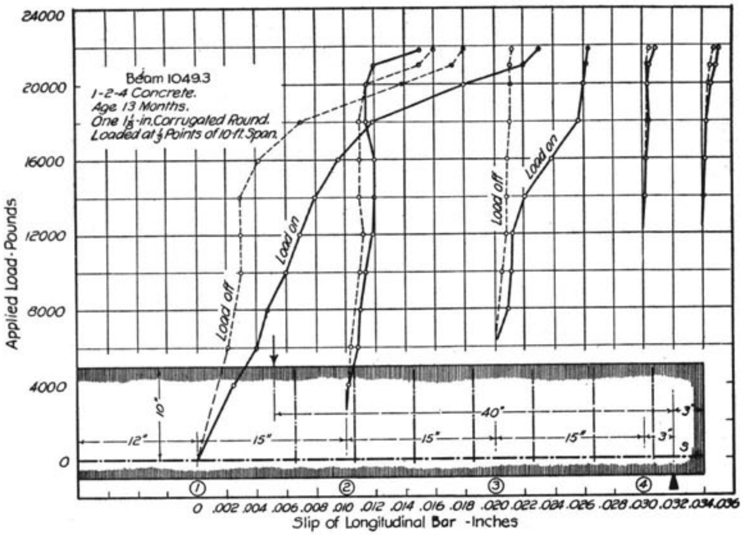
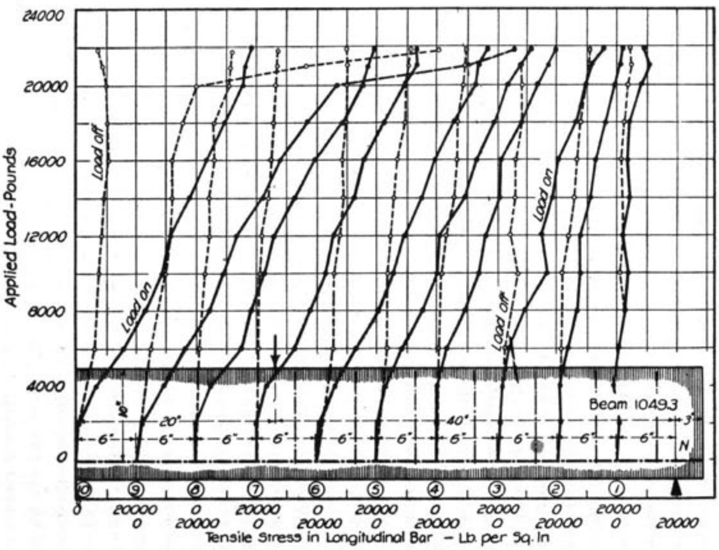


Fig. 65. Distribution of Tensile Stress in Bar in Beam No. 1055.3. One 1-in. Plain Round Bar; Span 10 ft.

points are the result of a single measurement, whereas in the tests described above the points represent the average of the values from both ends of the beam. At a load of 4000 lb., about one-fifth the maximum applied load, a bond stress of 137 lb. per sq. in. was being developed over the region (6) to (4) and an average of about 45 lb. per sq. in. over the 21-in. length at the end of the beam. The variation of bond stress throughout the test can be studied from the diagrams in Fig. 67 and from the values in Table 40. The observed bond stress over the region just outside the load point continued to rise until it reached 450 lb. per sq. in. at a load of 20 000 lb. Near the end of the beam the bond stress continued to rise until it reached 390 lb. per sq. in. at the maximum load of 21 900 lb. The highest bond stress observed over a considerable length of the bar in this test occurred be-

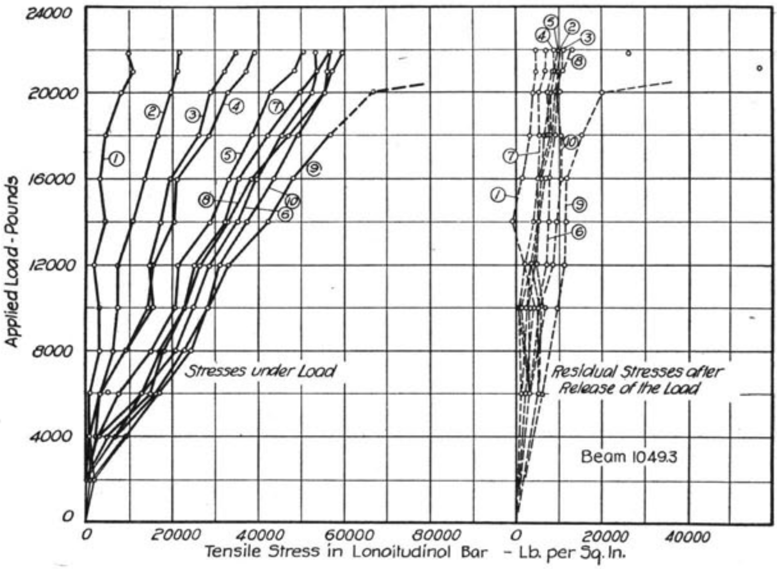


(a) Load-slip Curves for Longitudinal Bar.

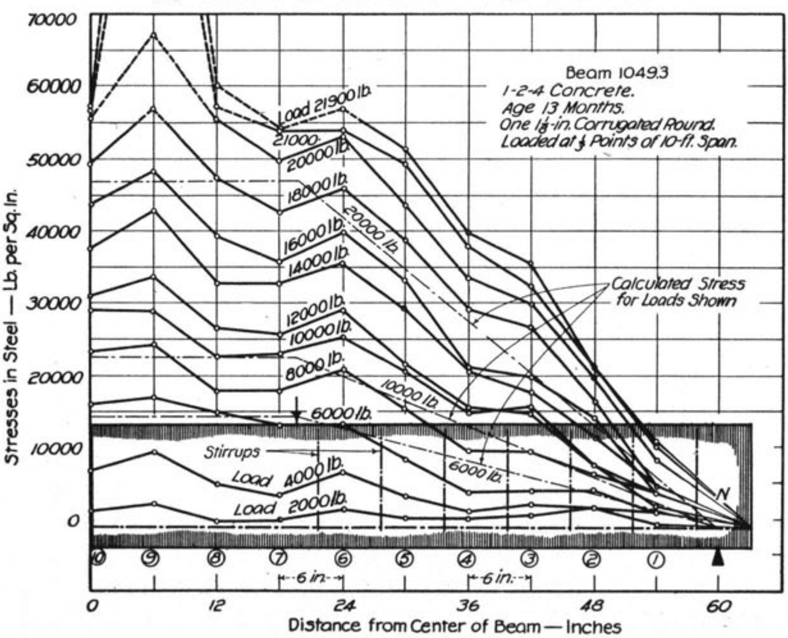


(b) Load-stress Curves for Longitudinal Bar.

FIG. 66. DIAGRAMS FROM TEST OF BEAM NO. 1049.3. ONE 1⅛-IN. CORRUGATED ROUND BAR; SPAN 10 FT.



(a) Load-stress Curves for Longitudinal Bar.



(b) Distribution of Tensile Stress in Longitudinal Bar.

FIG. 67. DIAGRAMS FROM TEST OF BEAM NO. 1049.3. ONE 1⅛-IN. CORRUGATED ROUND BAR; SPAN 10 FT.

tween (3) and (1) at the maximum load, and amounted to 580 lb. per sq. in. It is evident that stresses as high as this must have occurred at all points along the bar from the load point to (3) at some stage of the test, but the measurements were not sufficiently refined or the observations taken at sufficiently frequent intervals to detect such changes. This makes it apparent that there must be very rapid changes in the distribution of bond stress along the bar in a test of this kind. Fig. 66a shows the slip of bar at five points in Beam No. 1049.3. The amount of slip measured at any point depends to a large extent upon the proximity of cracks in the concrete and the load-slip curves may be expected to show considerable variation due to this cause. The residual slip after release of load is equal to about one-half the total slip up to a load of about 16 000 lb. The residual tensile stresses in the bar exhibit about the same characteristics as the residual slip-of-bar measurements. It is noteworthy that the residual tensile stresses over the larger portion of the length under observation did not increase much with increase of load after a load equal to about one-half the maximum had been applied. It is probable that a period of rest following the release of a load would have shown a material reduction in the residual stresses measured.

These tests show that the actual bond stresses developed in beams of this kind vary widely at all stages of the tests and that the bond stress calculated in the usual way represents the average stress, but does not indicate the extremes of stress in different portions of the span where beam bond stresses are present. The actual bond stresses developed varied from less than one-half to more than twice the calculated bond stress as determined in the usual manner.

As was pointed out in Art. 68, "Phenomena of Beam Tests," these tests indicate that at the early loads which develop the maximum beam bond resistance over a short length of bar outside the load points in beams in which the distance from the load to the support is as much as four times the effective depth, the bond stress developed near the ends of the bar may not be more than, say, 15% of the maximum bond resistance. The ratio of these stresses was not definitely determined, but the measurements of the tensile stress in the steel and the slip of bar indicate that the ratio given is approximately correct. It is probable that for longer beams the value would be found to be lower; in shorter beams the bond stress at the end of the bar when the maximum bond resistance was first developed outside the load points was probably as high as 40% of the maximum bond resistance.

In Fig. 68 is shown the distribution of bond and tensile stresses which may be expected in a reinforced concrete beam which fails by bond under two symmetrical loads. The curves indicate the changes which the stresses at different points undergo as the load is increased. In the region between the loads the tensile stress in the bar would be constant (disregarding the weight of the beam and the effect of anti-stretch slip) as indicated by the horizontal lines in the left portion of the figure. Between the load point and the support, the tensile stress at any point would be represented by the ordinates to the curves and the oblique lines, and the bond stress by the slope of these lines. The diagram indicates that the maximum beam bond resistance is first developed a short distance outside the load point at a load of 40% of the maximum load. The region over which the maximum bond resistance is being developed by a given load is indicated by the heavy solid lines. Since a bond stress much higher than the average is developed over a portion of the span, it is evident that at other points the bond stress must be less than the average. For a load 40% of the maximum the computed tensile stress outside the load point would be indicated by the ordinates to the dotted line KS, and the bond stress by the slope of this line, while the actual distribution of the tensile and bond stresses would be represented somewhat as shown by the curved solid line KS. This curve indicates that for a short distance outside the load point and near the support the bond stress is small, and that over a short length the maximum bond resistance is being developed. As the load is increased the region just outside the load point over which the bond stress is small is gradually extended and at the same time the portion of bar over which the maximum bond resistance is being developed is lengthened and pushed nearer the support. At the load causing failure by bond the actual stress in the bar is somewhat as shown by the line TLOS. In other words, the maximum bond resistance developed is represented to scale by MR instead of by LR as computed; and at failure this maximum stress was being developed over the length of bar PS, instead of over the length RS, as assumed by the usual methods of calculation. The parabolic line TS represents the theoretical stresses for a uniformly distributed load which produces the same maximum tensile stress at the mid-span as that produced by the concentrated loads shown. This curve suggests that a uniform load gives a more favorable condition for bond than concentrated loads. This is also evident from other considerations.

It is not intended that Fig. 68 should give a quantative indication of the distribution of stresses in any particular reinforced concrete beam. The presence of anti-stretch slip and the bond stresses due to this cause will greatly modify this distribution of stresses over certain regions of the span. However, it is clear that this somewhat idealized sketch does suggest the explanation of the discrepancy between the computed bond stresses in beam tests and the bond resistance found in other ways. The more accurate determination of the actual distribution of these stresses for beams of different make-up is a proper subject for further experimental study.

96. *Relation of Slip of Bar to Diagonal Tension Cracks.*—About 80 per cent of the beams reported in this bulletin failed in bond or an obvious combination of bond and diagonal tension. In many tests it was difficult to definitely assign the primary cause of failure, since the bar had shown considerable slip and at the same time there were evidences of failure from excessive diagonal tensile stresses in combination with the large slip. In assigning the manner of failure as shown in the tables, all the evidence of the test was considered—the slip of bar at the ends and at intermediate points, the size and position of cracks in the beam and the calculated stresses in the steel and concrete. In some of the tests the measurements gave indications of bond failure, but the calculated tensile stress in the bar and the cracks in the beam showed that the longitudinal steel was over-stressed at the middle of the span.

At failure nearly all of the beams except those of the longer spans showed one or two prominent diagonal cracks at one or both ends about midway between the load and the support. In Tables 28 and 34 the applied loads on the beam at the time of the observation of the first outer crack and at the first slip of the ends of the bar have been given in parallel columns. Reference to Fig. 69 to 76 and to Table 39 will show that slip of bar becomes appreciable at points about midway between the loads and the supports at loads about one-third the maximum for the beams reinforced with plain bars and loaded at the one-third points. For 25 tests on such beams the first visible crack outside the load points appeared at loads averaging 57% of the maximum and slip at the end began at 70% of the maximum load. These tests show that there is a considerable slip at the point where the diagonal cracks appear before these cracks became visible and indicated that the opening of these outer cracks was probably due primarily to slip of bar. The proportion of this slip due to beam bond stress and to anti-stretch slip will depend upon the dimensions and reinforcement of the beam. The bars used in these test beams were relatively large. The differences between the conditions in the middle third of the beam length and in the outer thirds should be kept in mind. In the middle region beam bond stress is not brought into action and the slip is wholly of the nature of what has been termed anti-stretch slip. In the outer thirds there is a combination of beam bond stress and of bond stress due to anti-stretch slip. The first outer crack generally became visible at a slip of bar of 0.002 to 0.005 in. It is evident that diagonal cracks may open at a very small slip of bar and that they open at loads which give very small end slip and even before end slip is noted. In the beams of Group 6 in which 4 in. of concrete was placed below the center of the bar, the cracks were restricted to the region within the load points or to a short distance outside (see Fig. 58a). The vertical shearing stresses developed were considerably higher than in other beams which were not reinforced with vertical stirrups.

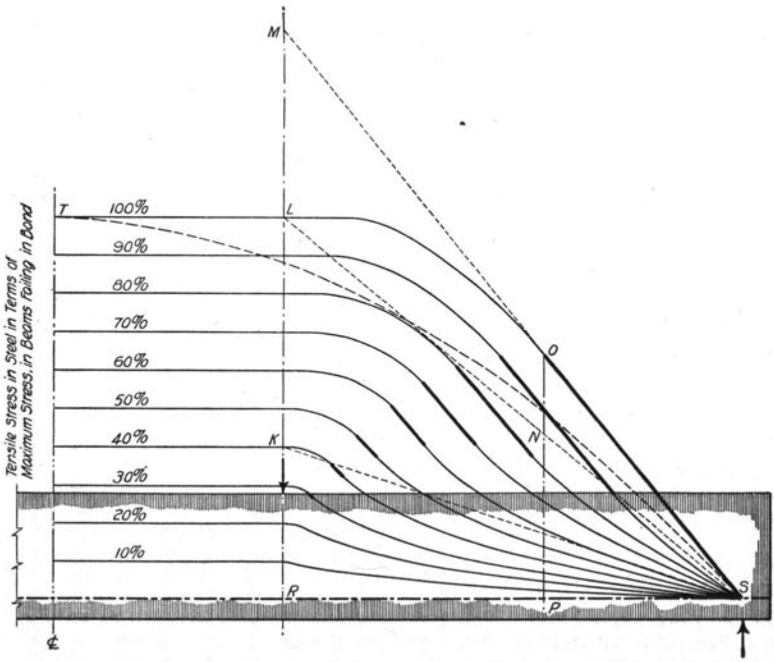


FIG. 68. IDEALIZED DIAGRAM SHOWING THE DISTRIBUTION OF TENSILE AND BOND STRESSES IN A SIMPLE REINFORCED CONCRETE BEAM.

97. *Influence of Slip of Bar upon Beam Deflection.*—Several treatises on reinforced concrete develop formulas which are intended to give expressions for the center deflection of a reinforced concrete beam, when the dimensions of the beam, the condition of the ends and the loading are known. These formulas will not be considered here, except to say that they are based on the usual deflection formula for homogeneous beams but modified to involve the assumptions that are commonly made in the analysis of reinforced concrete beams. These formulas show that beam deflection is a function of the loading, condition of the ends of the beam, span length, the elastic properties of the material and the dimensions of the section. With a combination of two materials having such different properties as concrete and steel and owing to the variation in the modulus of elasticity of concrete as the compressive stress increases, the deflection of a reinforced concrete beam is an extremely complex function. However, formulas have been devised which give fairly accurately the value of the deflection up to working loads if the proper value is assigned to the modulus of elasticity of the concrete.

One of the assumptions referred to above is that a plane section before flexure is a plane section after flexure. We have seen that during the greater part of the test of a reinforced concrete beam, slip of bar is an important phenomenon, and we may expect slip of bar to exert a marked influence on the deflection. Turneaure and Maurer,* in an investigation of deflection of reinforced concrete beams found that their formula gave values for deflection which were close to the true ones up to about one quarter of the maximum load carried by the beam. This is about the load at which slip of bar became pronounced through the middle portion of the span and we may expect that from this point the deflection is considerably influenced by slip of bar. As long as slip of bar is not general, there is no distinct change in the course of the load-deflection curve due to this cause, although its effect must be present from the time slipping begins. In homogeneous beams the additional deflection due to shear is neglected. In reinforced concrete beams the deflection due to slip of bar is an analogous quantity which has an important influence on the total deflection of the beam. As soon as slip of bar becomes general, as indicated by slip at the ends, we may expect the deflection to respond more rapidly to this cause. Many of the load-deflection curves in Fig. 77 to 86 show a decided in-

*Principles of Reinforced Concrete Construction, 1909.

crease in deflection immediately following the beginning of slip at the ends of the bar. Noteworthy examples of this action are found in Beam No. 1052.6, Fig. 81; Beam No. 1050.1, Fig. 84; Beam No. 1048.4, Fig. 86.

98. *Critical Bond Stress in Reinforced Concrete Beams.*—The foregoing discussions of beam tests in which slip of bar was measured indicate that slip of bar is found at relatively low loads. It was seen that slip of bar occurred first in the middle portion of the span at early loads. With increase of load slip of bar progresses through the outer thirds toward the ends. With the appearance of slip of bar at the ends of the beam, slip had become general through the region of beam bond stress and the beams were not able to permanently withstand a load appreciably greater than that causing first end slip. The tests indicate that a very small end slip may correspond to a critical bond stress.

The average bond stresses computed on the basis of the vertical shear are not the actual stresses being developed. As has already been pointed out, the tests show that maximum bond resistance is developed at certain points of the bar at loads much below that causing bond failure in the beam. Certain observations indicate that the bond stress first reaches the value of the maximum bond resistance in the portion of the span in which beam bond stresses are developed, at points a short distance outside of the load points. Anti-stretch slip may act to increase the bond stress developed over certain regions of the span. While slip of bar gives an indication of the bond stress being developed at any point as long as the amount of slip is small, it should be noticed that after the slip of bar has exceeded an amount corresponding to the maximum bond resistance further slip gives no indication of the amount of bond stress being developed.

99. *Working Stresses for Bond.*—The Committee on Concrete and Reinforced Concrete,* appointed by four of the leading American engineering societies (commonly known as the "Joint Committee") recommended the use of a bond stress equivalent to 4% of the compressive strength of the same concrete at 28 days of age for plain bars of ordinary mill surface and values one-half as great for drawn wire. The compressive strength of the concrete is to be determined from tests on 8 by 16-in. cylinders. For concrete giving a compressive strength of 2000 lb. per sq. in., at 28 days, the allowable bond stress is 80 lb. per sq. in. for

*See report in Proceedings of the American Society of Civil Engineers, Feb., 1913. Also Proceedings of the American Society for Testing Materials, 1913, p. 228.

plain bars. These values have been generally accepted by American designers. The British Joint Committee on Reinforced Concrete† recommended the use of a bond stress of 100 lb. per sq. in. in concrete having a compressive strength of 1800 lb. per sq. in. when tested in the form of cubes not less than 4 in. on a side or cylinders not less than 6 in. in diameter and of a length not less than the diameter. Tests recently made at the University of Illinois on compression specimens of different forms show that the compressive strength of 6-in. concrete cubes is about 27% higher than that of 8 by 16-in. cylinders. On this basis the British Committee's concrete would have a compressive strength about 70% of the American Committee's concrete and the allowable working bond stress would be about 80% higher than the corresponding values of the American Committee, considering the quality of the concrete.

It was seen in Art. 48 that the average bond stress in the pull-out tests when end slip began was about 17% of the compressive strength of 6-in. cubes made from the same concrete. Reducing this to the basis used above, we may say that slip began in the pull-out tests at a bond stress equal to about 13% of the compressive strength of 8 by 16-in. cylinders. In the same way the ultimate bond resistance in the pull-out tests discussed in Art. 48 was about 19% of the compressive strength of 8 by 16-in. cylinders. Certain of the beam tests indicate that the actual bond resistance of a bar embedded in a reinforced concrete beam was not materially different from that of pull-out specimens made in the same position. The working stress recommended by the American Joint Committee is equal to about ⅓ the bond stress corresponding to first slip of bar and to about 1/5 the ultimate pull-out resistance of plain bars. Apparently this indicates a factor of safety of about 3 against slip of bar, if we consider first slip of bar in the region where beam bond stresses are developed as the critical stress. However, we have seen that on account of the unequal distribution of bond stress in beams loaded at the one-third points, the bond stresses actually developed over a short length outside the loads is probably near the ultimate bond resistance even for working loads at the age of the beams tested. This in reality may not be a serious consideration since there should be a sufficient reserve of bond resistance in the embedded portion of the bar where the

†See Second Report Joint Committee on Reinforced Concrete, published by the Royal Institute of British Architects, 1911.

bond stress is low, and an additional reserve in the increasing bond resistance with the increase in the age of the concrete. From the way in which the steel stress is distributed in Fig. 64 to 67, it would seem that the stress conditions of a beam under a uniformly distributed load are more favorable to bond resistance than the system of concentrated loads used in the tests. It would appear that the values of working stresses for bond recommended by the British Committees are entirely too high considering the grade of concrete. The values of the American Committee are as high as should be used under average conditions of workmanship.

The data for beams reinforced with deformed bars are not as complete as for plain bars, but on account of the undesirable secondary stresses which are introduced in the concrete as a result of high bond stresses, it seems the part of wisdom to use the same values for deformed as for plain bars. However, it should be recognized that properly designed deformed bars may be expected to give a greater uniformity of steel stress than plain bars, and they may be counted upon to guard against local deficiencies in bond resistance due to lack of care in placing the concrete around the bars or to other defects due to poor workmanship.

IV. Summary.

100. *Summary.*—The tests covered a wide range of conditions and the results have a significant bearing on the nature of bond resistance, the action of bars of different forms under bond stress, and the behavior of beams subjected to high bond stresses. The load-slip determinations have given definite information on the nature and distribution of bond resistance. The following is a resumé of the principal observations and conclusions which have been stated and discussed in the text. Paragraphs 2 to 34, inclusive, refer primarily to the results of the pull-out tests.

(1) Bond between concrete and steel may be divided into two principal elements, adhesive resistance and sliding resistance. The source of adhesive resistance is not known, but its presence is a matter of universal experience with materials of the nature of mortar and concrete. Sliding resistance arises from inequalities of the surface of the bar and irregularities of its section and alignment together with the correspond-

ing conformations in the concrete. The adhesive resistance must be overcome before sliding resistance comes into action. In other words, the two elements of bond resistance are not effective at the same time at a given point. Many evidences of the tests indicate that adhesive resistance is much the more important element of bond resistance.

(2) Pull-out tests with plain bars show that a considerable bond stress is developed before a measurable slip is produced. Slip of bar begins as soon as the adhesive resistance is overcome. After the adhesive resistance is overcome, a further slip without an opportunity of rest is accompanied by a rapidly increasing bond stress until a maximum bond resistance is reached at a definite amount of slip.

(3) The true relation of slip of bar to bond stress can best be studied by considering the action of a bar over a very short section of the embedded length. The difficulties arising from secondary stresses made it impracticable to conduct tests on bars embedded very short lengths. The desired results were obtained by varying the forms of the specimens in such a way that the effect of different combinations of dimensions could be studied.

(4) Pull-out tests with plain bars of the same size embedded different lengths furnish data which suggest the values of bond resistance over a very short length of embedment, or indicate values of bond resistance which are independent of the length of embedment. Tests with bars of different size which were embedded a distance proportional to their diameters give the true relation when the effect of size of bar is eliminated. Two series of tests of this kind on plain round bars of ordinary mill surface gave almost indentical values for bond resistance after eliminating the effect of length of embedment and size of bar, and we may consider that these values represent the stresses which were developed in turn over each unit of area of the embedded bar as it was withdrawn by a load applied by the method used in these tests. These tests showed that for concrete of the kind used (a 1-2-4 mix, stored in damp sand and tested at the age of about 60 days) the first measurable slip of bar came at a bond stress of about 260 lb. per sq. in., and that the maximum bond resistance reached an average value of 440 lb. per sq. in. If we conclude that adhesive resistance was overcome at the first measurable slip, it will be seen that the adhesive resistance was about 60% of the maximum bond resistance. This ratio did not vary much for a wide range of mixes, ages, size of bar, condition of storage, etc.

(5) Sliding resistance reached its maximum value for plain bars of ordinary mill surface at a slip of about 0.01 in. The constancy in the amount of slip corresponding to the maximum bond resistance for a wide range of mixes, ages, sizes of bar, conditions of storages, etc., is a noteworthy feature of the tests. With further slip the sliding resistance decreased slowly at first, then more rapidly, until with a slip of 0.1 in. the bond resistance was about one-half its maximum value.

(6) Pull-out tests with plain round bars show end slip to begin at an average bond stress equal to about one-sixth the compressive strength of 6-in. cubes from the same concrete; the maximum bond resistance is equal to about one-fourth the compressive strength of 6-in. cubes. These values were about the same for a wide range of mixes, ages and conditions of storage. In terms of the compressive strength of 8 by 16-in. concrete cylinders these values would be about 13% for first end slip and 19% for the maximum bond resistance.

(7) The tests indicate that bond stress is not uniformly distributed along a bar embedded any considerable length and having the load applied at one end. Slip of bar begins first at the point where the bar enters the concrete, and the bond stress must be greater here than elsewhere until a sufficient slip has occurred to develop the maximum bond resistance at this point. Slip of bar begins last at the free end of the bar. After slip becomes general, there is an approximate equality of bond stress throughout the embedded length.

(8) Small bars gave a bond resistance somewhat higher than the large bars during the early stages of the test. This was probably on account of greater irregularity of section and alignment of the smaller bars. The maximum bond resistance was not materially different for bars of different diameters.

(9) Computations based on the elastic properties of the materials indicate that in the pull-out tests the tensile deformation in the bar had a much greater effect on the amount of bond stress which permitted a given slip of bar than had the compressive deformation in the concrete block in which the bar was embedded.

(10) Rusted bars gave bond resistances about 15% higher than similar bars with ordinary mill surface.

(11) The tests with flat bars showed wide variations of bond resistance and were not conclusive. Square bars gave values of unit-stress about 75% of those obtained with plain round bars.

(12) T-bars gave lower unit bond resistance than plain round bars, but gave about double the bond resistance per unit of length that was found for the plain round bars of the same sectional area.

(13) With polished bars the bond resistance is due almost entirely to adhesion between the concrete and steel. Numerous tests with polished bars embedded in 1-2-4 concrete and tested at 60 days indicated a maximum bond resistance of about 160 lb. per sq. in., or about 60% of the bond resistance of bars of ordinary surface at small amounts of slip. This value agrees closely with tests reported elsewhere, and apparently represents the value of the tangential adhesion between any clean steel and concrete of this quality. The sliding resistance of polished bars was very low.

(14) Tests with polished bars with wedging and non-wedging tapers showed that adhesion was broken for both types of bar at about the same bond stress as in the polished bars of uniform section.

(15) The tests with polished bars with wedging taper showed that after the adhesion was broken a considerable movement of the bar (as much as ¼ in. with the smallest tapers) was required before the bond resistance again reached the amount which was at first carried by the adhesive resistance. The amount of movement necessary to restore the bond stress to the value of the original adhesive resistance was inversely proportional to the amount of taper. This indicates that a definite normal compression must be developed in the surrounding concrete before a longitudinal component equivalent to the original tangential adhesion is produced.

(16) It was noted in the tests with plain bars that sliding resistance was due to inequalities of the surface of the bar and to irregularities of its section and alignment. The projections on a deformed bar give an exaggerated condition of inequality of surface or irregularity of section. Adhesive resistance must be destroyed and the usual sliding resistance largely overcome and the concrete ahead of the projections must undergo an appreciable compressive deformation before the projections on a deformed bar become effective in taking bond stress. The tests indicate that the projections do not materially assist in resisting a force tending to withdraw the bar until a slip has occurred approximating that corresponding to the maximum sliding resistance of plain bars. As slip continues a larger and larger portion of the bond stress is taken by direct bearing of the projections on the concrete ahead.

(17) In determining the comparative merits of deformed bars, the bar which longest resists beginning of slip should be rated highest, other considerations being equal. The bond stresses developed at an end slip of 0.001 inch furnished the principal basis of comparison for the different types of deformed bars. At an end slip of 0.001 in. 12 sets of deformed bars of ¾-in. and larger sizes embedded 8 in. in 1-2-4 concrete, tested at about 2 months, developed an average bond resistance of 318 lb. per sq. in., 4% higher than the corresponding value for plain bars. At this stage of the test, two sets of deformed bars gave practically the same bond resistance, five sets gave lower values, and five sets higher values than the plain rounds. At an end slip of 0.01 in., corresponding to the maximum bond resistance of plain bars, the average bond resistance of the 12 sets of deformed bars was 445 lb. per sq. in., 10% higher than plain rounds. At this stage of the test two sets gave about the same values, two sets gave lower values, and eight sets gave higher values than the plain bars. The hooping used in these specimens had a marked effect in increasing the bond resistance even at small amounts of slip.

(18) The concrete cylinders of the pull-out specimens with deformed bars were reinforced against bursting or splitting, because it was desired to study the load-slip relation through a wide range of values. The bond stresses corresponding to an end slip of 0.1 in. are the highest stresses reported for the deformed bars. In only a few tests was the maximum bond resistance reached at an end slip less than 0.1 in. It should be recognized that, in general, the bond stresses reported for deformed bars at end slip of 0.05 and 0.1 in., could not have been developed with bars embedded in unreinforced blocks. These high values of bond resistance must not be considered as available under the usual conditions of bond action in reinforced concrete members. In the tests in which the blocks were not reinforced, evidence of splitting of the blocks was found at end slips of 0.02 to 0.05 in.

(19) The normal components of the bearing stresses developed by the projections on a deformed bar may produce very destructive bursting stresses in the surrounding concrete. The bearing stress between the projections and the concrete in the tests with certain types of commercial deformed bars was computed to be from 5800 to 14 000 lb. per sq. in. at the highest bond stresses considered in these tests. For bars having projections of different heights and spacing, the bearing stresses on the projections at the highest bond stresses considered were inversely proportional to the bond stress which had been developed by the bar at an end

slip of 0.01 in., the slip at which the projections were beginning to be effective. These considerations show that the ratio of the area of the projections measured at right angles to the bar to the superficial area of the bar in the same length is the proper criterion for judging of the effective bond resistance of a deformed bar. In some forms of bar the bearing stresses must have been much higher than the values given above. The large slip and the high bearing stresses developed in the later stages of the tests show the absurdity of seriously considering the extremely high values that are usually reported to be the true bond resistance of many types of deformed bars.

(20) Round bars with standard V-shaped threads gave much higher bond resistance at low slips than the commercial deformed bars. The average bond resistance at an end slip of 0.001 in. was 612 lb. per sq. in. The maximum bond resistance was 745 lb. per sq. in. These were the only deformed bar tests in which failure came by shearing the surrounding concrete.

(21) In a deformed bar of good design the projections should present bearing faces as nearly as possible at right angles to the axis of the bar. The areas of the projections should be such as to preserve the proper ratio between the bearing stress against the concrete ahead of the projections and the shearing stress over the surrounding envelope of concrete. Failure by shearing of the concrete should be avoided. The tests indicate that the areas of the projections measured at right angles to the axis of the bar should not be less than, say, 20% of the superficial area of the bar. A closer spacing of the projections than is used in commercial deformed bars would be of advantage. Advocates of the deformed bar would do well to recognize the fact that in a deformed bar which may be expected to develop a high bond resistance, a certain amount of metal must be used in the projections which probably will not be available for taking tensile stress.

(22) The 1-in. twisted square bars gave a bond resistance per unit of surface at an end slip of 0.001 in., only 88% of that for the plain rounds. Following an end slip of about 0.01 in., these bars showed a decided decrease in bond resistance, and a slip of 5 to 10 times this amount was required to cause the bond resistance to regain its first maximum value. After this, the bond resistance gradually rose as the bar was withdrawn. Some of the bars were withdrawn 2 or 3 in. before the highest resistance was reached. The apparent bond stresses at these slips were very high; but, of course, such stresses and slips could

not be developed in a structure and could not have been developed in the tests had the blocks not been reinforced against bursting. Such values are entirely meaningless under any rational interpretation of the tests.

(23) The load-slip curves for twisted square bars are similar to those for polished bars with wedging taper. The twisted bar is essentially a combination of the wedging and non-wedging taper. As the bar is drawn through the concrete the wedging tapers are drawn more firmly against the concrete ahead, while at the same time the non-wedging tapers are separated from the concrete with which they were originally in contact. The drop in the load-slip curves after an end slip of about 0.01 in. shows that the separation of about one-half of the surface of the bar from its original contact and the continued sliding of the flatter portions of the bar, until a large slip has occurred, have a greater influence in reducing the average bond resistance than the increased bearing of the wedging tapers has in raising the bond resistance. The results found with the twisted square bar do not justify its present widespread popularity as a reinforcing material.

(24) The tests with plain round bars anchored by means of nuts and washers and with washers only showed that the entire bar must slip an appreciable amount before these forms of anchorage come into action. Anchorages of the dimensions used in these tests did not become effective until the bar had slipped an amount corresponding to the maximum bond resistance of plain bars. With further movement the apparent bond resistance was high, but was accompanied by excessive bearing stresses on the concrete.

(25) The load-slip relation for bars anchored by means of hooks and bends was not determined. The high resistance given in these tests was probably a result of the bearing stresses developed in the concrete ahead of the bends.

(26) Tests on specimens stored under different conditions indicate that concrete stored in damp sand may be expected to give about the same bond resistance and compressive resistance as that stored in water. Water-stored specimens gave values of maximum bond resistance higher in each instance than the air-stored specimens; the increase for water storage ranged from 10 to 45%. The difference seemed to increase with age. The presence of water not only did not injure the bond for ages up to three years, but it was an important factor in producing conditions which resulted in high bond resistances. However, it was found that

specimens tested with the concrete in a saturated condition gave lower values for bond than those which had been allowed to dry out before testing. The bars in specimens which had been immersed in water as long as three and one-half years showed no signs of rust or other deterioration.

(27) Specimens made out-doors in freezing weather, where they probably froze and thawed several times during the period of setting and hardening, were almost devoid of bond strength.

(28) Pull-out tests made at early ages gave surprisingly high values of bond resistance. Plain bars embedded in 1-2-4 concrete and tested at 2 days did not show end slip of bar until a bond stress of 75 lb. per sq. in. was developed. Bond resistance increases most rapidly with age during the first month. The richer mixes show a more rapid increase than the leaner ones. The tests on concrete at ages of over one year showed that the bond resistance of specimens stored in a damp place may be expected ultimately to reach a value as much as twice that developed at 60 days.

(29) The load-slip relation of leaner and richer mixes was similar to that for 1-2-4 concrete. For a wide range of mixes the bond resistance was nearly proportional to the amount of cement used. This relation did not obtain in a mix from which the coarse aggregate had been omitted.

(30) When the application of load was continued over a considerable period of time or when the load was released and reapplied, the usual relation of slip of bar to bond resistance was considerably modified. The few tests which were made indicate that the bond stress corresponding to beginning of slip is the highest stress which can be maintained permanently or be reapplied indefinitely without failure of bond. The effect of continued and repeated load, impact, etc., may well be the subject of further experimental study.

(31) Little difference was found in the pull-out tests whether the load was distributed over the entire face of the block or over a narrow ring at the center of the block or around the edge of the face of the block.

(32) Specimens molded in a horizontal position gave lower bond resistance than those molded in a vertical position; when settlement of the bar with the settlement of the concrete was entirely prevented, the bond resistance was reduced to about 60% of that found for similar specimens which were molded with the bars in a vertical position. Plain

bars tested by being pulled in the same or the opposite direction from the settlement of the concrete during setting gave about the same bond resistance, but in the tests of certain deformed bars this was not true.

(33) The term "autogenous healing" is used to designate phenomena observed in pull-out tests and in compression tests of concrete cylinders in which the hardening of the concrete was interrupted by loading the specimen at early ages to its ultimate resistance. Up to an age of one year the bond resistance of specimens stored in damp sand was not affected by as many as four loadings at intervals during the period of storage up to the ultimate resistance. For specimens stored in air and tested in the same way, the bond resistance was less than for damp-sand storage, but the tests showed a steady increase in bond resistance with each loading up to three months. Specimens which had been stored in air for two months before the first test and in water thereafter showed a decrease in bond with each subsequent loading, although the bond resistance in the last test was fairly high. The presence of water apparently permits the continuation of the hydraulic action of the cement for several months after the mixing of the concrete.

(34) Bond resistance of plain bars is greatly increased if the concrete is caused to set under pressure. With a pressure of 100 lb. per sq. in. on the fresh concrete for five days after molding, the maximum bond resistance was increased 92% over that of similar bars in concrete which had set without pressure. The greater density of the concrete and its more intimate contact with the bar seems to be responsible for the increased bond resistance. Light pressures gaves an appreciable increase in bond resistance. With polished bars the effect of pressure was slight.

(35) As might have been expected, the compressive resistance of concrete setting under pressure was increased in much the same ratio as the bond resistance. At the age of 80 days the initial modulus of elasticity in compression for concrete which set under a pressure of 100 lb. per sq. in. was about 37% higher and the compressive strength was increased by about 73% over that of concrete which had set without pressure. The density of the concrete, as determined by the unit weights, was increased about 4% by a pressure of 100 lb. per sq. in. on the fresh concrete. The increase in strength and density was relatively greater for the low than for the high pressures. A pressure continued for one day, or until the concrete had taken its final set and hardening had begun, seems to have produced the same effect in increasing the

strength and elastic properties of the concrete as when the pressure was continued for a much longer period.

(36) Concrete cylinders tested in compression at age of 80 days after having been loaded to failure at 7 days gave compressive strengths nearly as high as those tested for the first time at the same age. Retests of cylinders which had set under pressure gave similar results.

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(37) Beams of comparatively short span reinforced with bars of large size were used in order to develop high bond stresses and give bond failures. Most of the beams failed in bond; a few failed by a combination of bond and diagonal tension or by tension in the steel.

(38) The usual method of computing the bond stress in a reinforced concrete beam does not take account of all the phenomena of bond action. Slip of bar due to beam bond action and the presence of anti-stretch slip may be expected to greatly modify the distribution of bond stress over the length of the bar, and otherwise to affect resistance to beam bond stresses. However, the nominal values for bond resistance, computed by the usual formula, form a useful basis for comparison in beams in which the dimensions and general make-up are similar.

(39) Slip of bar was a phenomenon in all beam tests in which careful slip observations were made. These load-slip relations give important indications as to the bond stress developed at points along the length of the beam.

(40) Slip was first observed in the middle region of the span at loads producing a tensile stress in the steel of about 6000 lb. per sq. in. In this region the shear is zero and hence beam bond action, as usually understood, is absent. As the load was increased, slip of bar progressed through the outer thirds toward the ends of the beam at a rate nearly proportional to the increase of load. After slip occurred at the ends, the outer thirds of the length of the bar moved toward the middle of the span relative to the adjacent concrete. Slip of bar was probably partly responsible for the opening of outer cracks, since slipping was observed in the outer thirds of the beams before the cracks became visible.

(41) The mean computed values for bond stresses in the 6-ft. beams in the series of 1911 and 1912 were as given below. All beams were of 1-2-4 concrete, tested at 2 to 8 months by loads applied at the one-third points of the span. Stresses are given in pounds per square inch.

	Number of Tests	First End Slip of Bar	End Slip of 0.001 in.	Maximum Bond Stress
1 and 1¼-in. plain round..............	28	245	340	375
¾-in. plain round.....................	3	186	242	274
⅝-in plain round......................	3	172	235	255
1-in. plain square....................	6	190	248	278
1-in. twisted square..................	3	222	289	337
1⅛-in. corrugated round..............	9	251	360	488

(42) In the beams reinforced with plain bars end slip begins at 67% of the maximum bond resistance; for the corrugated rounds this ratio is 51%, and for the twisted squares, 66%.

(43) The bond unit resistance in beams reinforced with plain square bars, computed on the superficial area of the bar, was about 75% of that for similar beams reinforced with plain round bars of similar size.

(44) Beams reinforced with twisted square bars gave values at small slips about 85% of those found for plain rounds. At the maximum load, the bond-unit stress with the twisted bars was 90% of that with plain round bars of similar size.

(45) In the beams reinforced with 1⅛-in. corrugated rounds, slip of the end of the bar was observed at about the same bond stress as in the plain bars of comparable size. At an end slip of 0.001 in., the corrugated bars gave a bond resistance about 6% higher and at the maximum load, about 30% higher than the plain rounds.

(46) The beams in which the longitudinal reinforcement consisted of three or four bars smaller than those used in most of the tests gave bond stresses which, according to the usual method of computation, were about 70% of the stresses obtained in the beams reinforced with a single bar of large size. The progressive opening of cracks with increase in load was well shown in these tests. These beams showed cracks nearer the ends than usual. The distances of the outermost cracks from the ends of the beams suggest that the unbroken length of embedment has an important bearing on the maximum loads which the beams may be expected to carry before failing by bond. It seems probable that the lower computed bond stresses in these tests are due to errors in the assumptions made as to the distribution of bond stress and not to actual differences of bond resistance in the bars of different size.

(47) The tests on beams with the loads placed in different positions with respect to the span gave little variation in bond resistance during the early stages of the tests. The maximum bond resistances increased rapidly as the load approached the supports. These tests indicate that the variation in the maximum bond stresses must be due to the presence of other than normal beam action.

(48) Nearly all the beams tested on span lengths of 7 to 10 ft. failed by tension in the steel and did not develop the maximum bond resistance, although high bond stresses were obtained. The bond stress corresponding to first end slip of bar did not vary much with the span length.

(49) The bond stresses developed in the beam tests indicate that with beams of the same cross-section the bond stresses are distributed in the same way during the early stages of the test in beams varying widely in span length and loading. During the later stages of the test, the distribution of bond stress seems to depend largely upon the conditions of stress in the concrete through the region of the span where beam bond stresses are high. The distribution of bond stresses in beams of different cross-section apparently varies with the relative dimensions of the beam and the reinforcing bars.

(50) The use of auxiliary tensile reinforcement in the outer thirds of the beam served to modify the distribution of bond stress during the early stages of the test, but did not have any influence on the maximum bond resistance. While the auxiliary bars seemed to prevent the opening of outer cracks, the tests indicate that interior cracks which did not appear on the surface of the beam may have opened to an extent that permitted the same distribution of bond stress as was found in other tests.

(51) Increasing the thickness of the concrete below the reinforcing bars beyond the depth usually employed caused a very large increase in the resistance to bond and web stresses. The added stiffness of the beam and the increased flexural strength through the outer thirds of the span, prevented the formation of cracks in these regions. In the other beam tests such cracks were found to interrupt the continuity of bond action and to be an important factor in producing lower average bond resistances.

(52) Increasing the length of overhang of the ends of the beam beyond the support did not increase the resistance to web stresses as indicated by the opening of outer cracks, but it had an influence on the bond resistance. The bond resistance at first end slip was greater in the beams with the longer overhang. The maximum bond resistance was materially increased by the additional overhang.

(53) In the reinforced concrete beams it was found that very small amounts of slip at the ends of the bar represented critical conditions of bond stress. For beams failing in bond the load at an end slip of 0.001 in. was 89% to 94% of the maximum load found in beams

reinforced with plain bars, and 79% of the maximum load for similar beams reinforced with corrugated bars. As soon as slip of bar became general, other conditions were introduced which soon caused the failure of the beam.

(54) The bond stresses developed in a reinforced concrete beam by a load applied as in these tests varies widely over the region in which beam bond stresses are present. High bond stresses are developed just outside the load points at comparatively low loads. The load which first developed a bond stress nearly equal to the maximum bond resistance in the region of beam bond stresses produced a stress near the support which was not more than about 15 to 40% of the maximum bond resistance. As the load is increased, the region of high bond stress is thrown nearer and nearer the support, and at the same time the bond stress over the region just outside the load point becomes steadily smaller. This indicates a piecemeal development of the maximum bond stress as the load is increased. The actual bond stresses in certain tests varied from less than one-half to more than twice the average bond resistance computed in the usual manner.

(55) Slip of bar in a reinforced concrete beam has a marked influence in increasing the center deflection during the later stages of loading.

(56) The comparison of the bond stresses developed in beams and in pull-out specimens from the same materials is of interest. Such a comparison should be made for similar amounts of slip. In the pull-out tests the maximum bond resistance came at a slip of about 0.01 in. for plain bars. The mean bond resistance for the deformed bars tested was not materially different from that of the plain bars until a slip of about 0.01 in. was developed; with a continuation of slip the projections came into action and with much larger slip high bond stresses were developed. The beam tests showed that about 79 to 94% of the maximum bond resistance was being developed when the bar had slipped 0.001 in. at the free end; hence the bond stress developed at an end slip of 0.001 in. was used as a basis of the principal comparisons in the pull-out tests. However, it is recognized that, under certain conditions, the stresses developed at larger amounts of slip may have an important bearing on the effective bond resistance of the bar.

(57) The pull-out tests and beam tests gave nearly identical bond stresses for similar amounts of slip in many groups of tests, but it seems that this was the result of a certain accidental combination of dimensions in the two forms of specimens and did not indicate that the com-

puted stresses in the beams were the correct stresses. However, it is believed that a properly designed pull-out test does give the correct value of bond resistance, and gives values which probably closely represent the bond stresses which actually exist in a beam or other member as slipping is produced from point to point along the bar. The relative position of the bar during molding may be expected to influence the values of bond resistance found in the tests.

(58) A properly made pull-out test on a specimen of correct design is a valuable aid in determining the bond resistance of reinforcing steel in concrete, if due consideration is given to the load-slip relation. The tensile stress in the bar should be kept well below the elastic limit. Best results will be obtained by using a relatively short embedment. An embedment of 8 diameters is recommended.

(59) A working bond stress equal to 4% of the compressive strength of the concrete tested in the form of 8 by 16-in. cylinders at the age of 28 days (equivalent to 80 lb. per sq. in. in concrete having a compressive strength of 2000 lb. per sq. in.) is as high a stress as should be used. This stress is equivalent to about one-third that causing first slip of bar and one-fifth of the maximum bond resistance of plain round bars as determined from pull-out tests. The use of deformed bars of proper design may be expected to guard against local deficiencies in bond resistance due to poor workmanship and their presence may properly be considered as an additional safeguard against ultimate failure by bond. However, it does not seem wise to place the working bond stress for deformed bars higher than that used for plain bars.

101. *Concluding Remarks.*—The tests described in this bulletin have thrown considerable light on the value of bond resistance and the distribution of bond stress for a wide range of conditions in both beam and pull-out tests. It may not be expected that all of the results indicated can be applied without modification to members in which the conditions of stress differ widely from those present in the tests.

Most of the foregoing discussions and conclusions are based on comparisons involving the load-slip relations. In a few of the tests the bond stress was determined from a study of the variations in the tensile stress in the reinforcing bar. The latter method furnishes a much more direct means of measuring the bond stress, but it has been available only since the recent development of a non-fixed extensometer. Additional tests are planned which are expected to give further information on this subject.

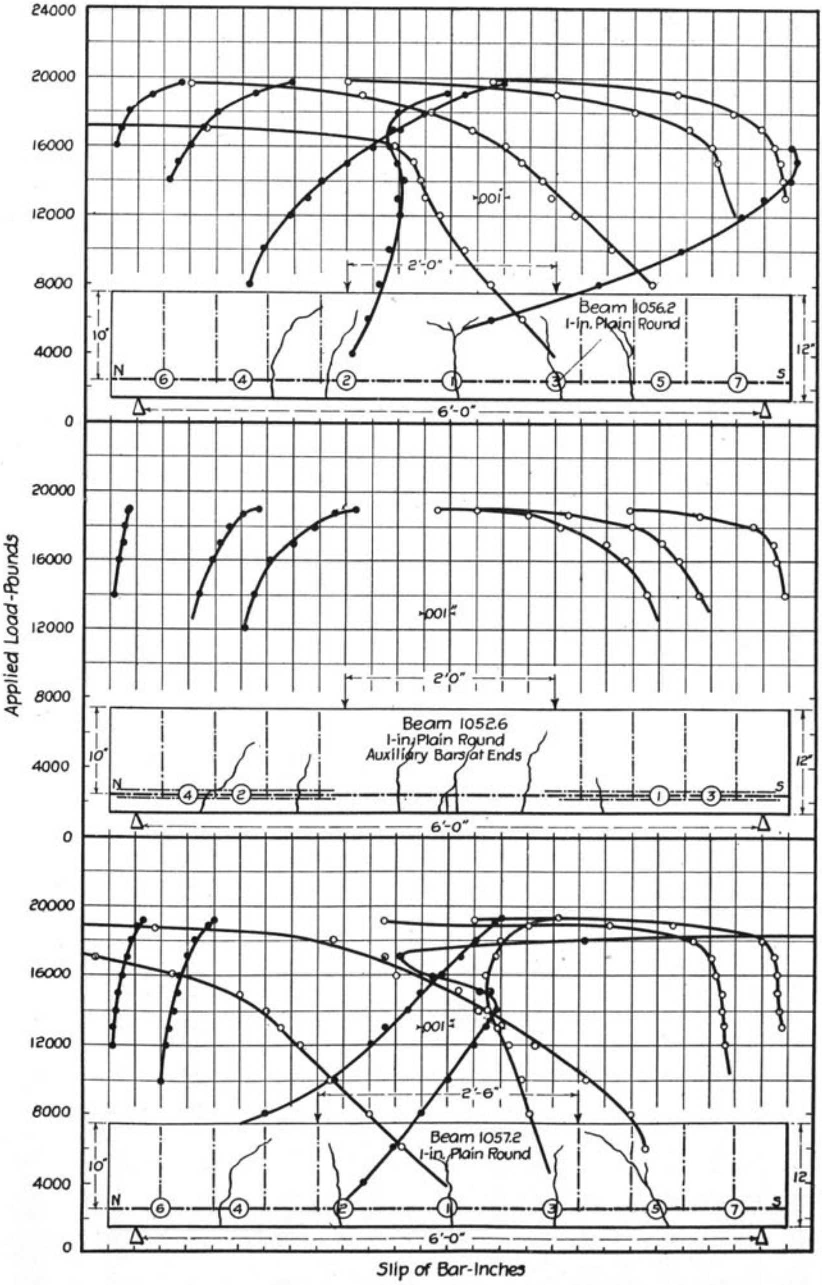

FIG. 69. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

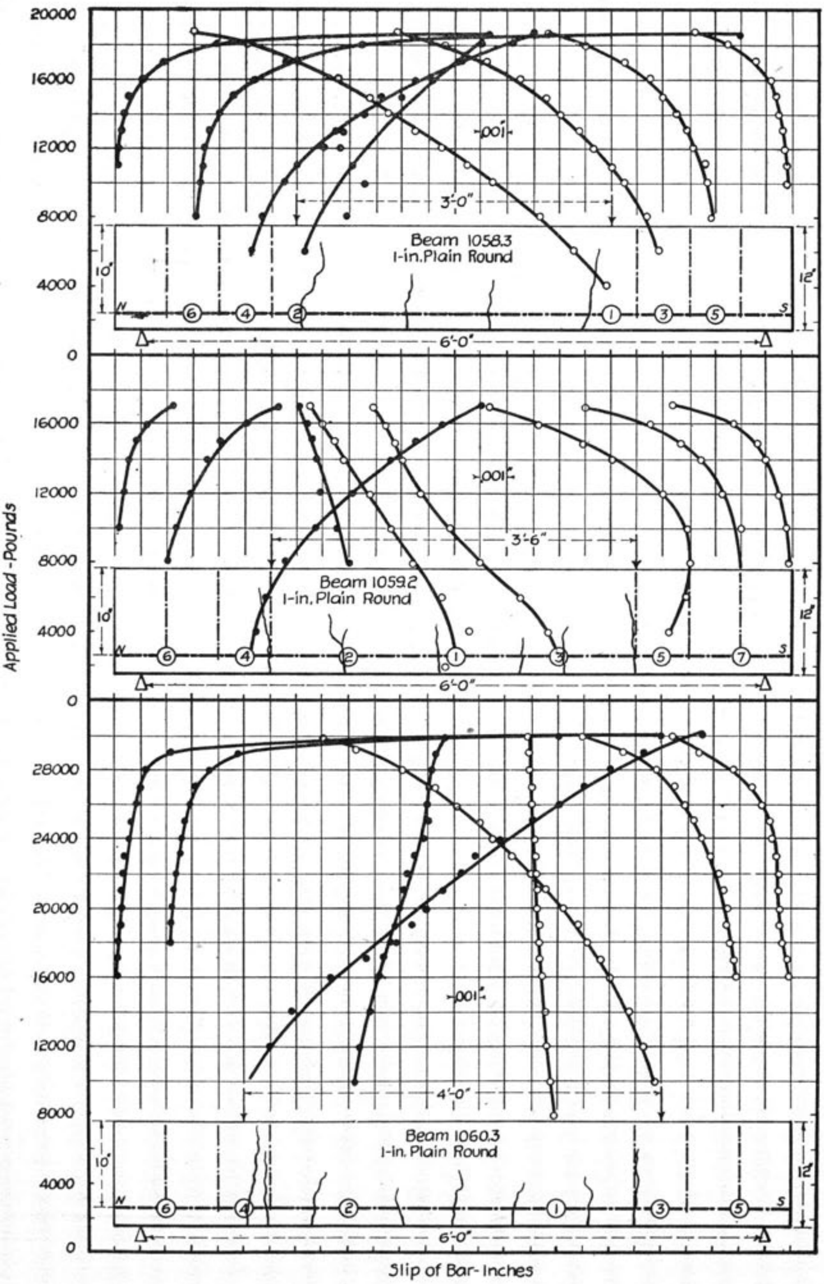

FIG. 70. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

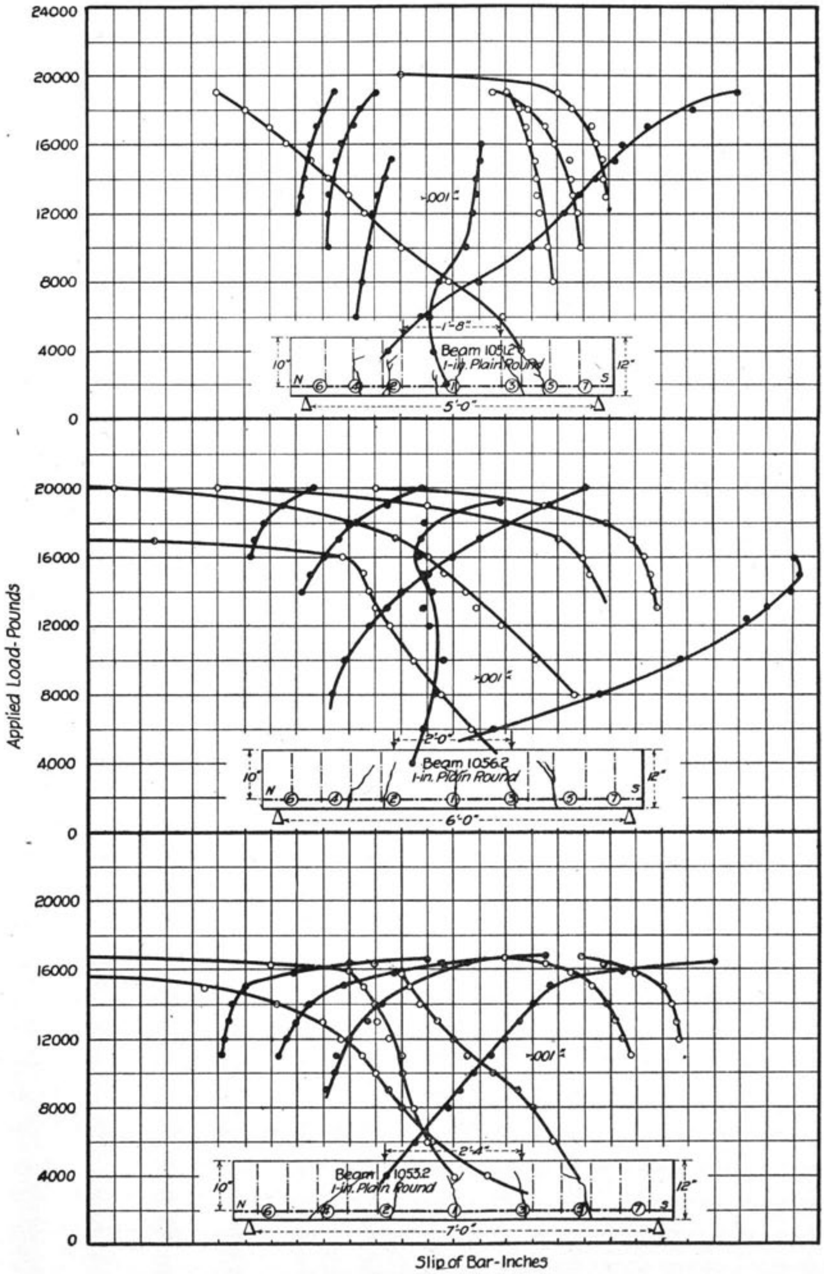

FIG. 71. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

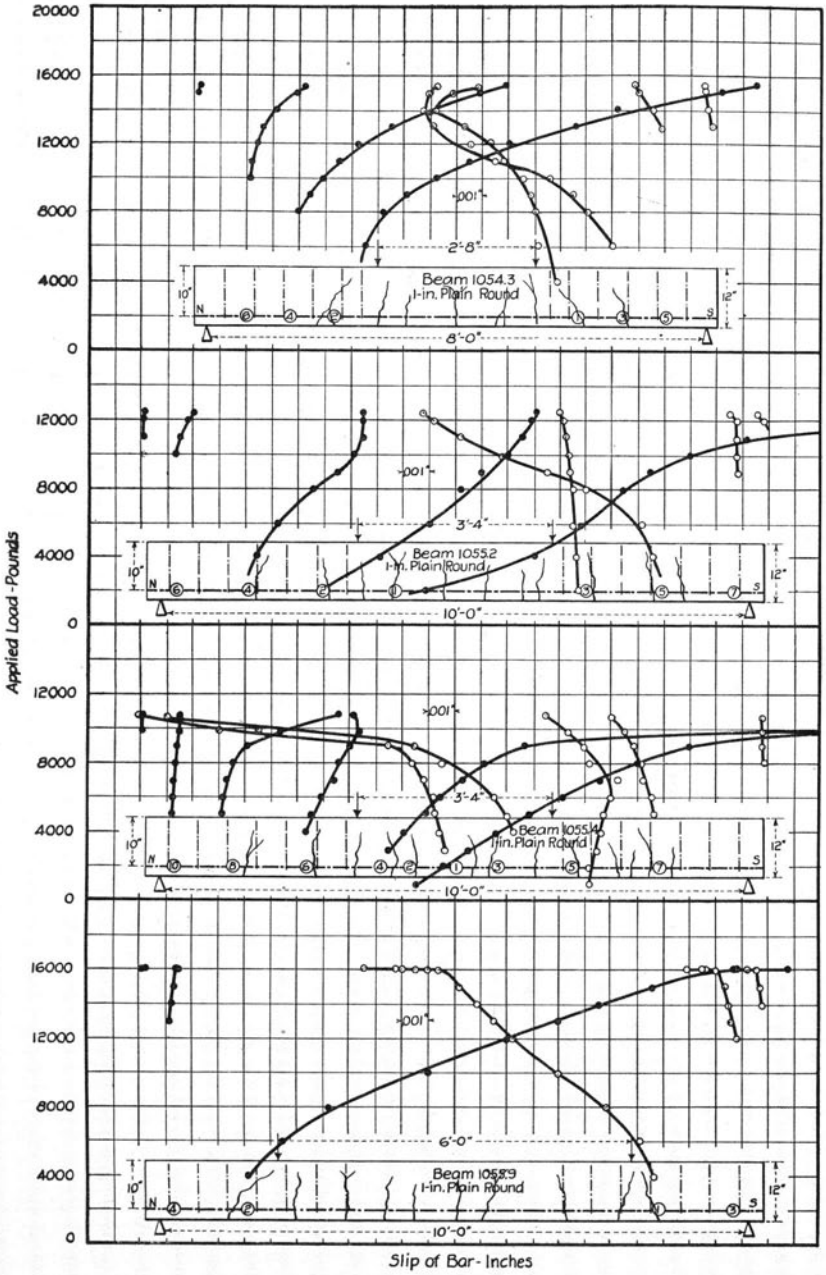

FIG. 72. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

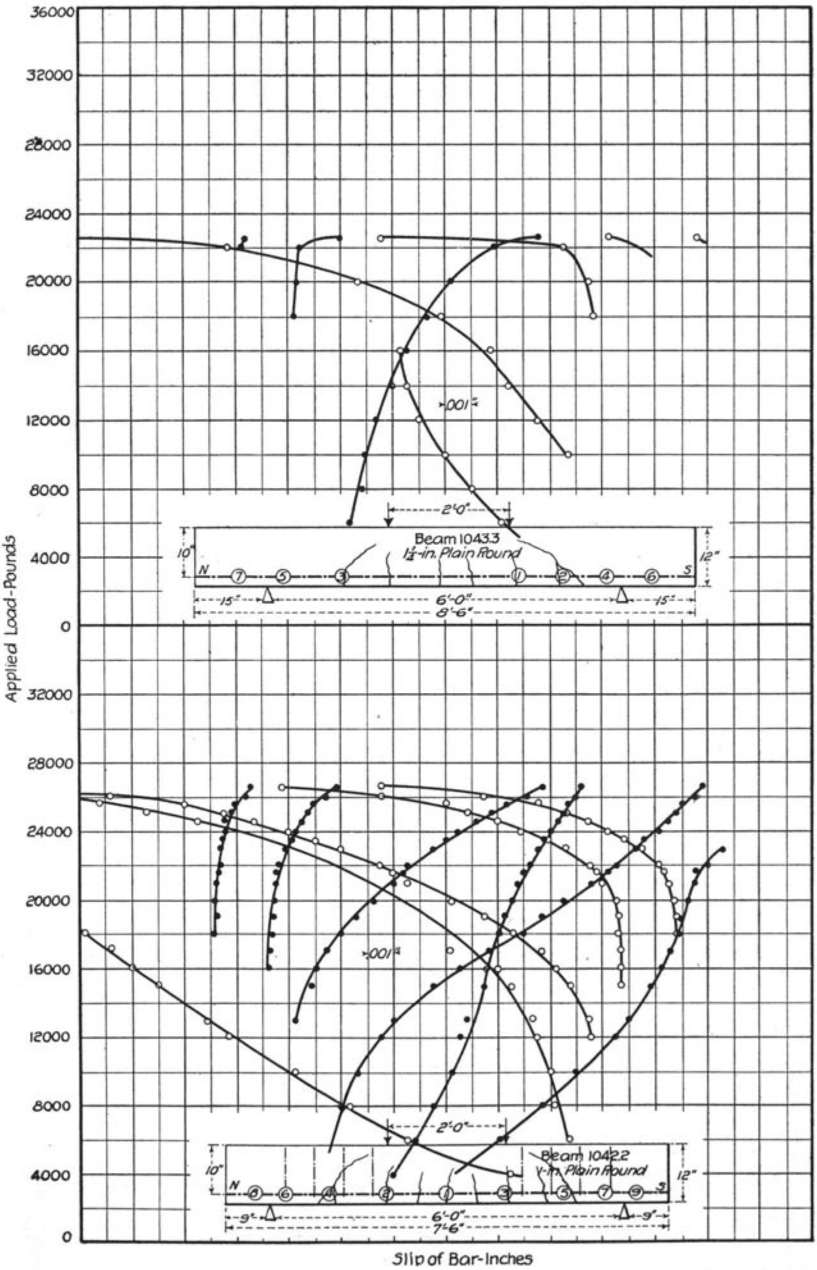

FIG. 73. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

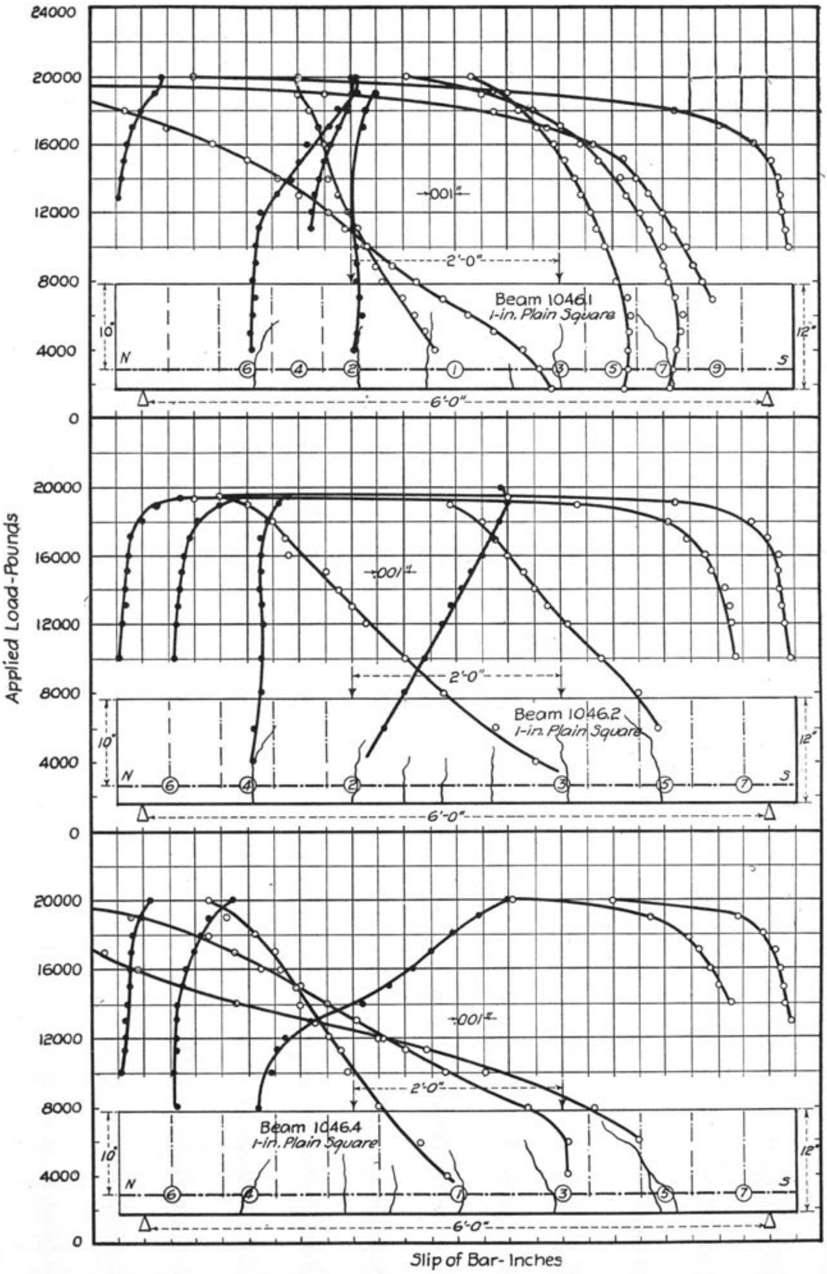

FIG. 74. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

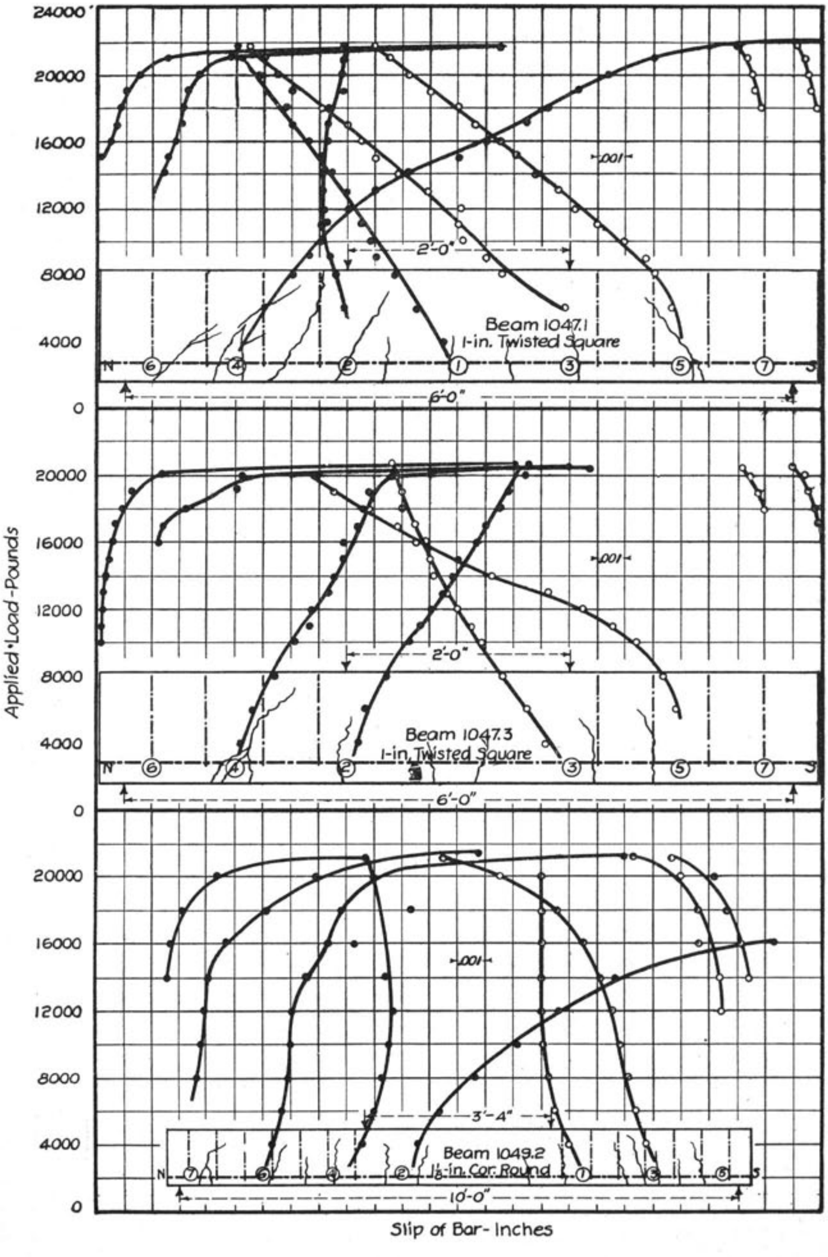

FIG. 75. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

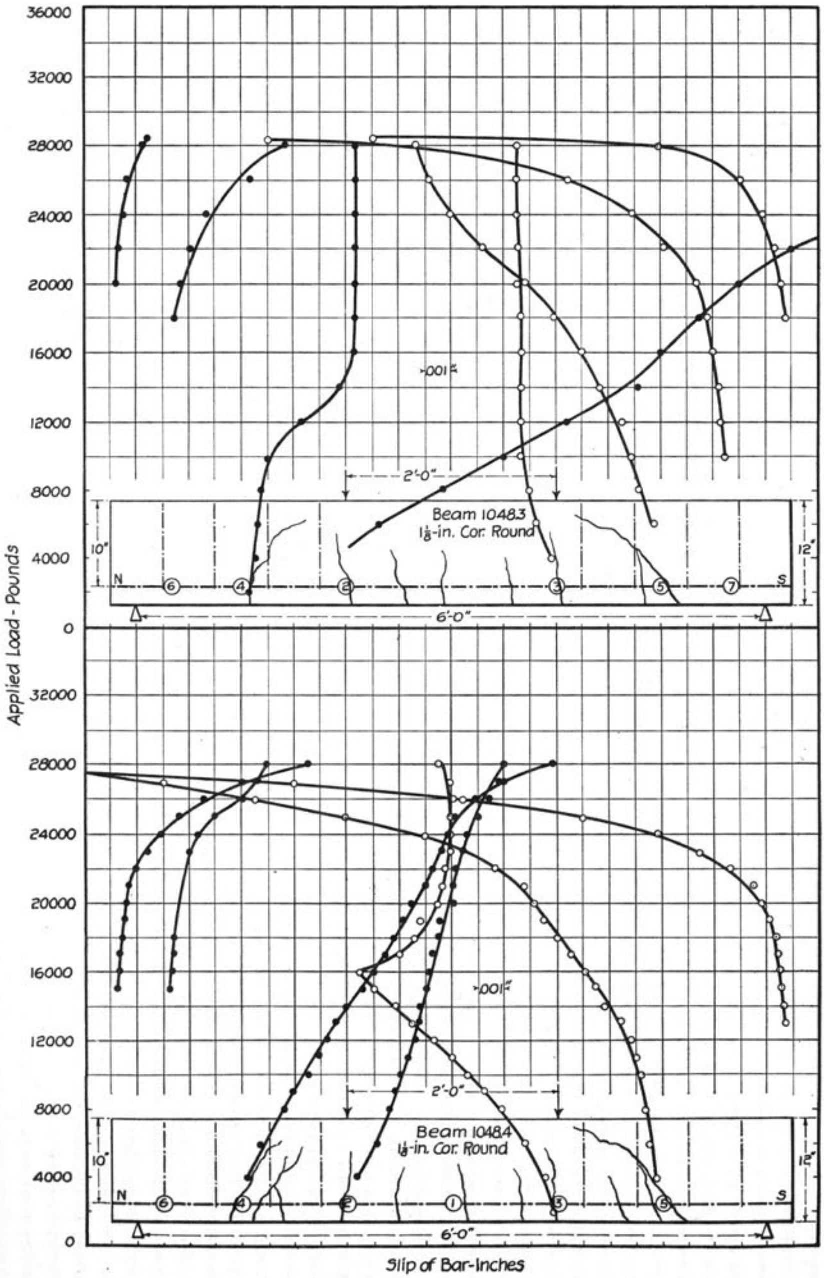

FIG. 76. LOAD-SLIP CURVES FOR BARS IN REINFORCED CONCRETE BEAMS.

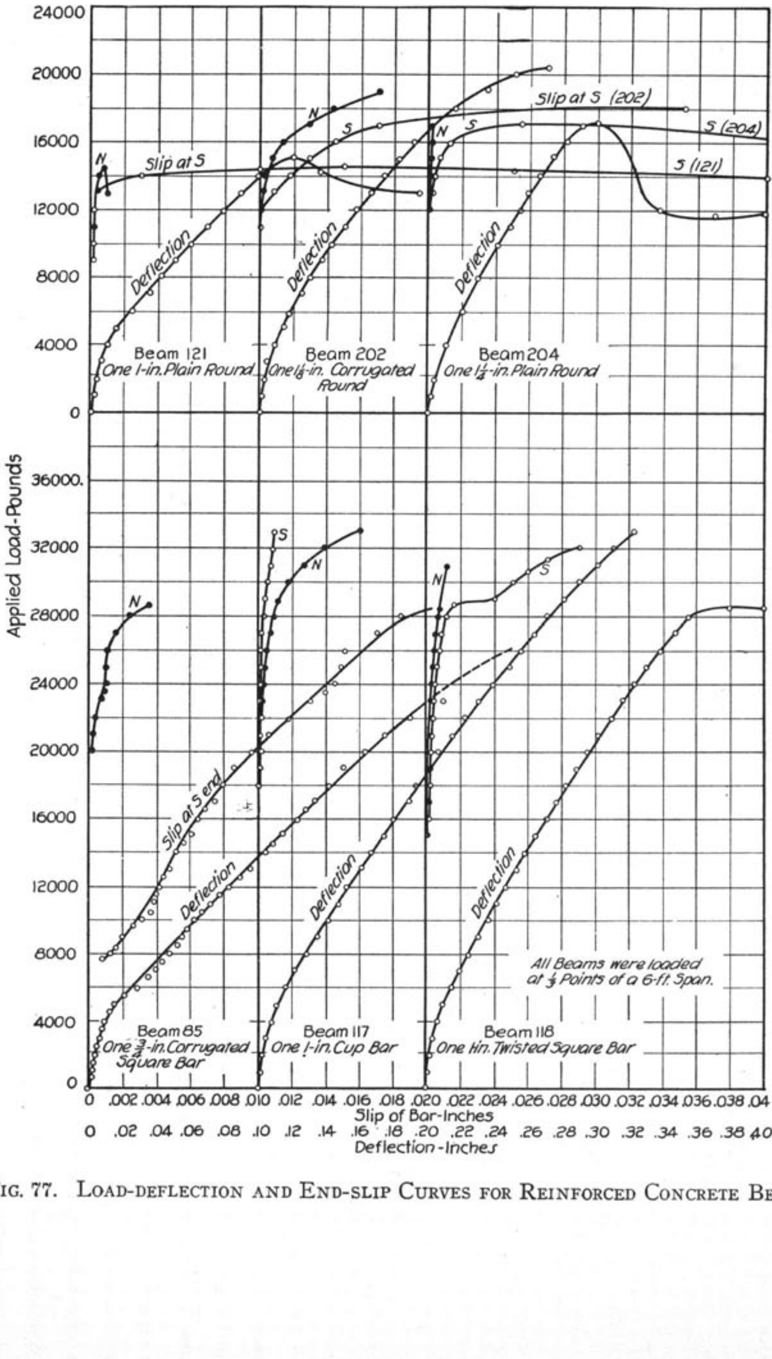

FIG. 77. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

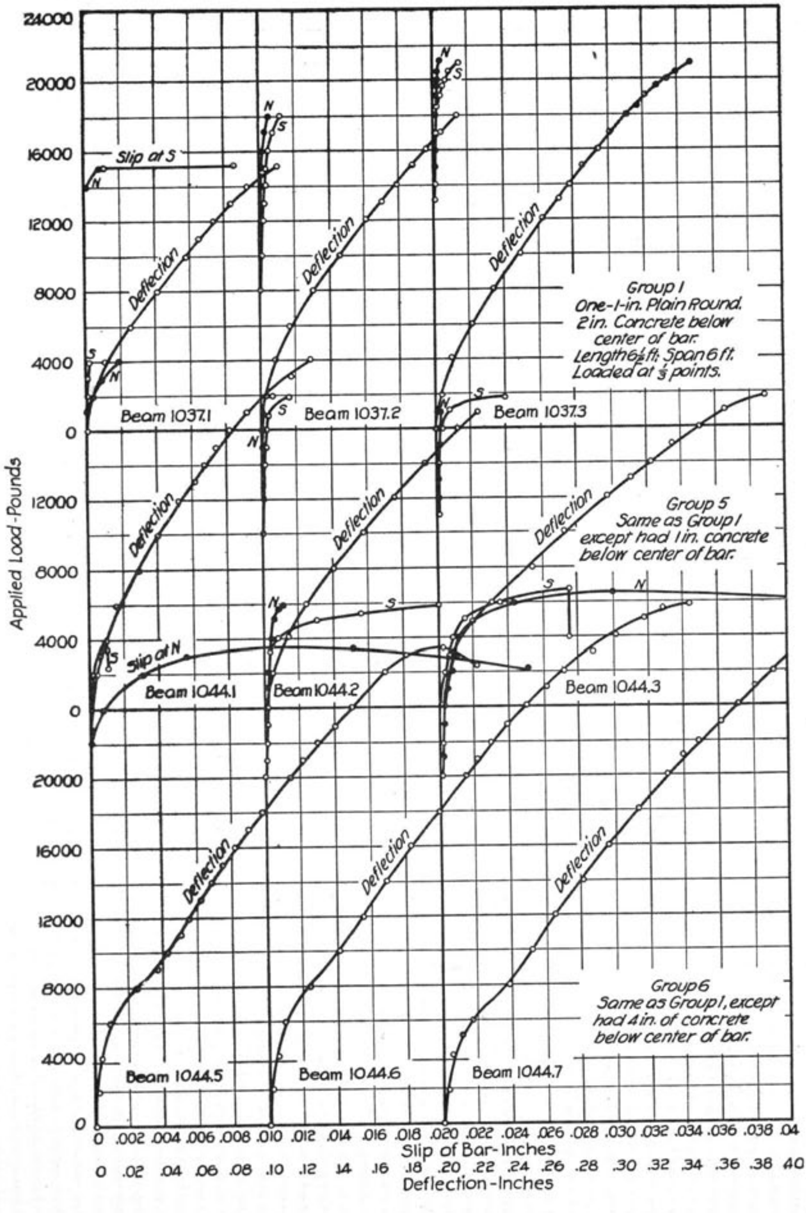

Fig. 78. Load-deflection and End-slip Curves for Reinforced Concrete Beams.

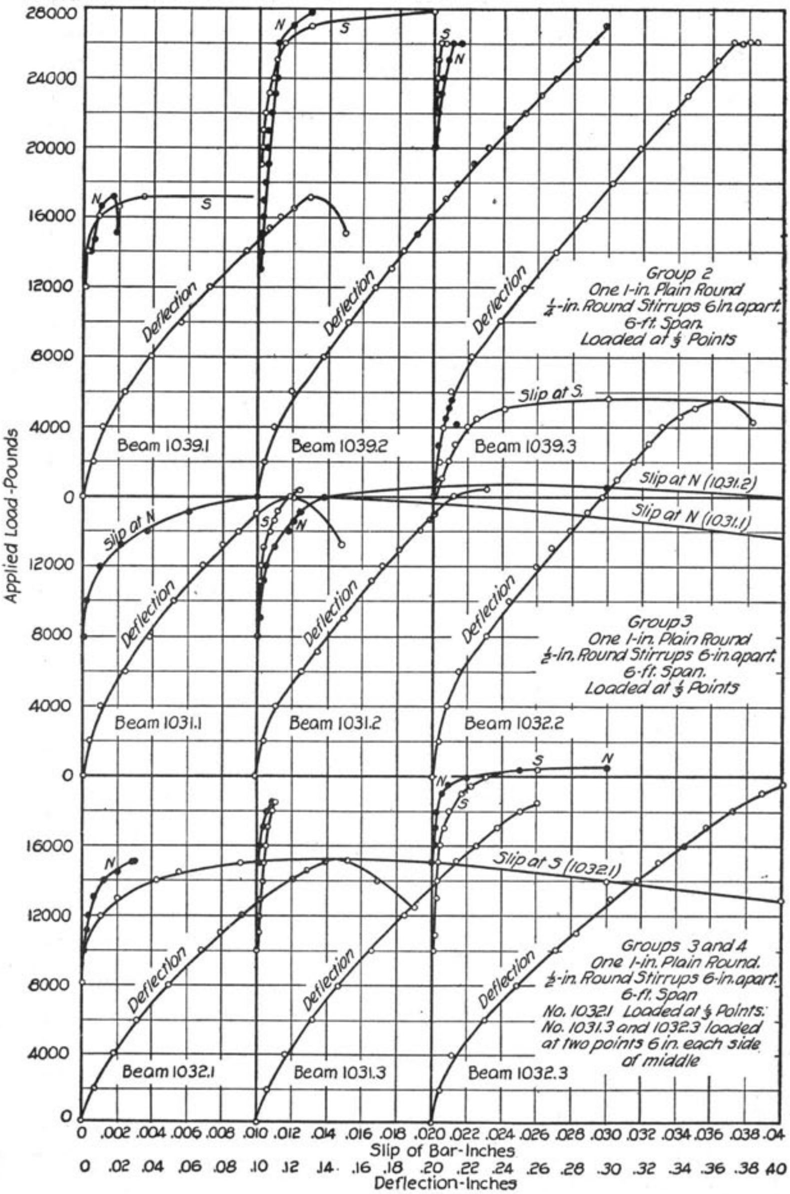

FIG. 79. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

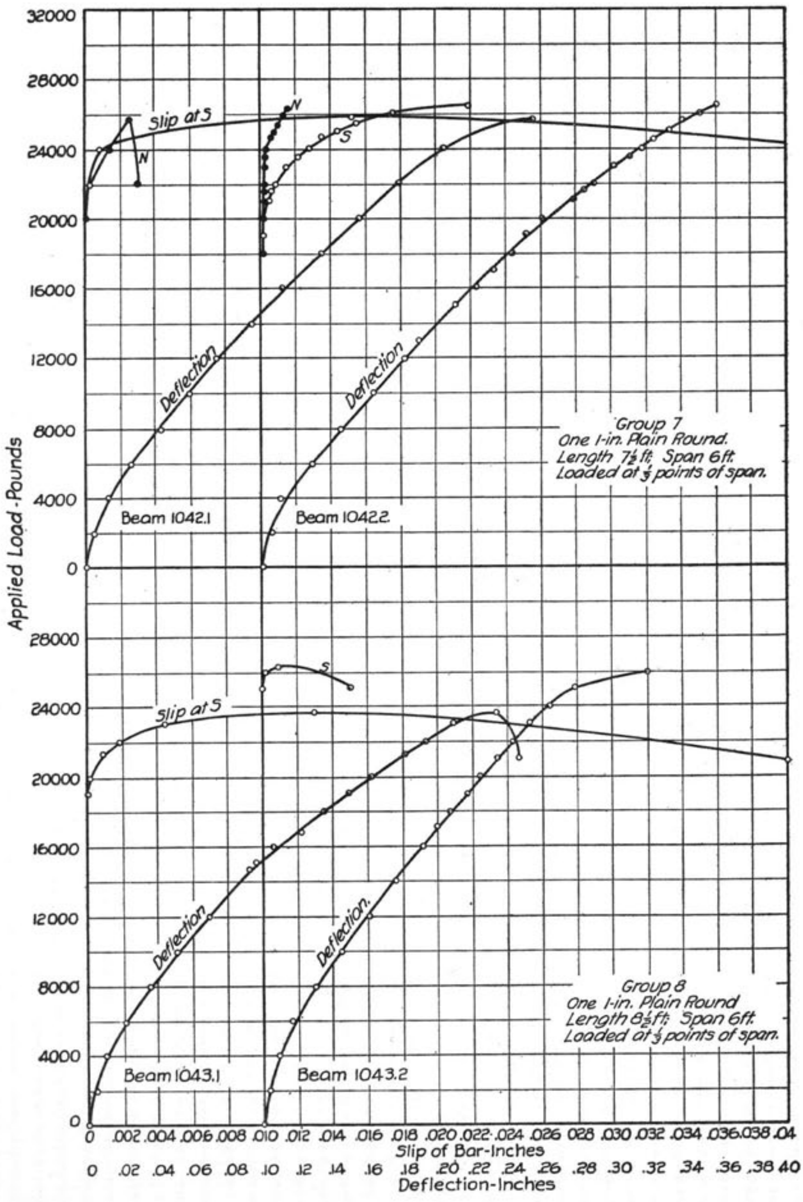

FIG. 80. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

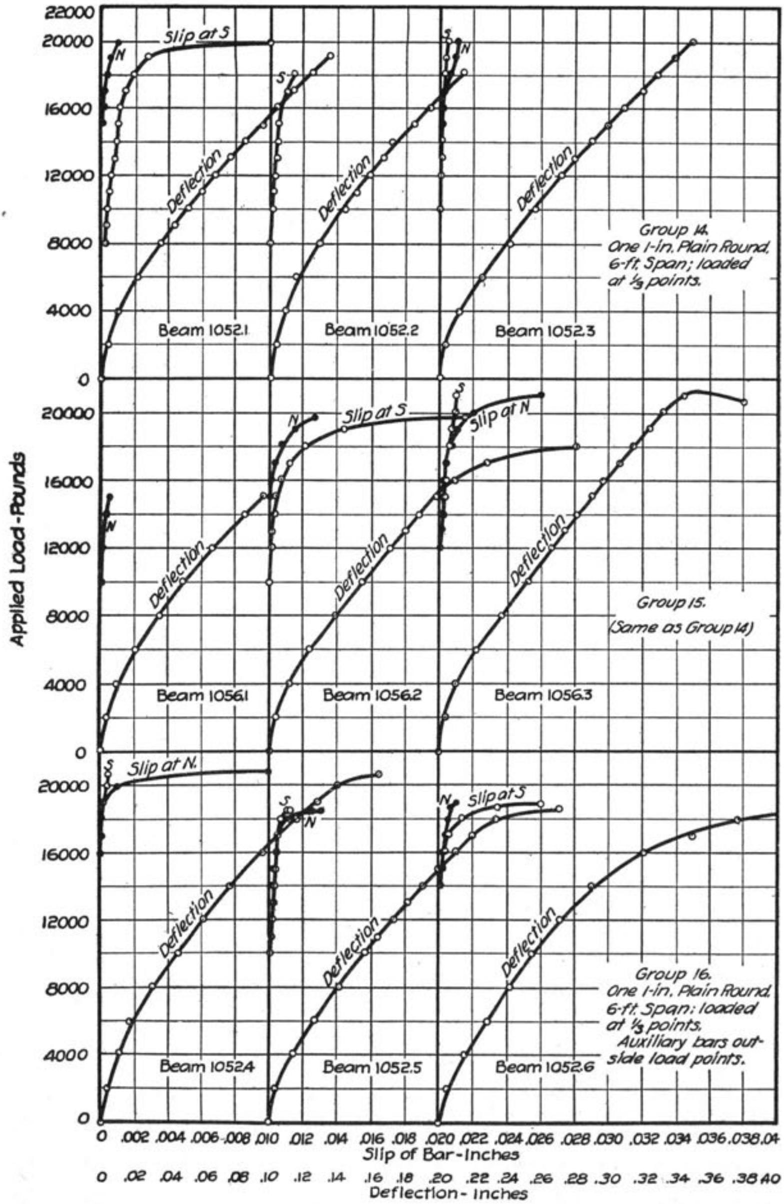

FIG. 81. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

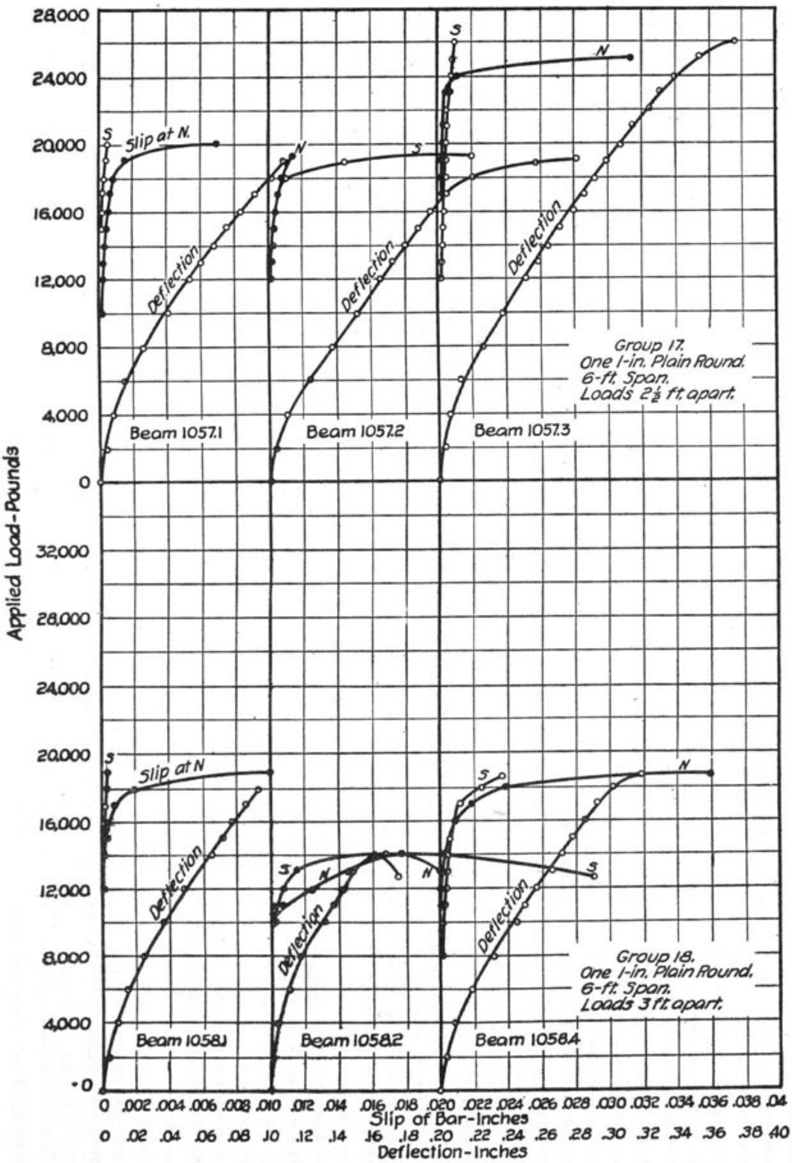

FIG. 82. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

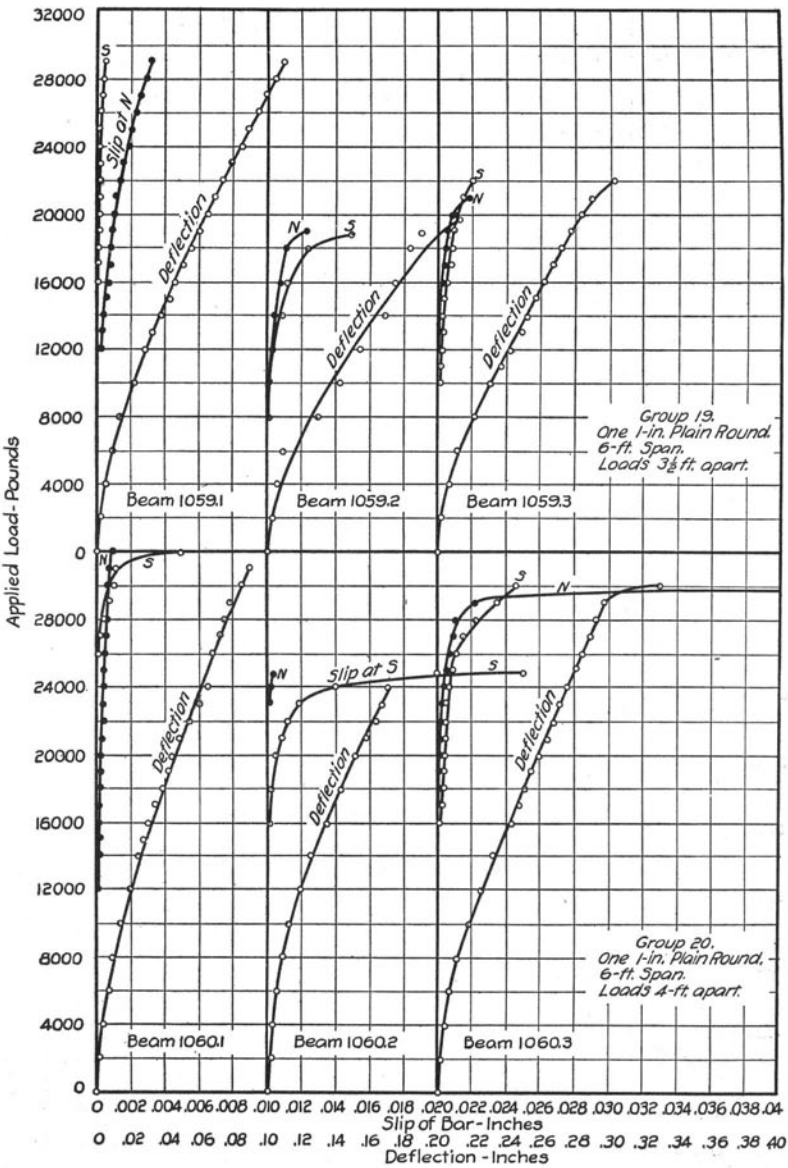

FIG. 83. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

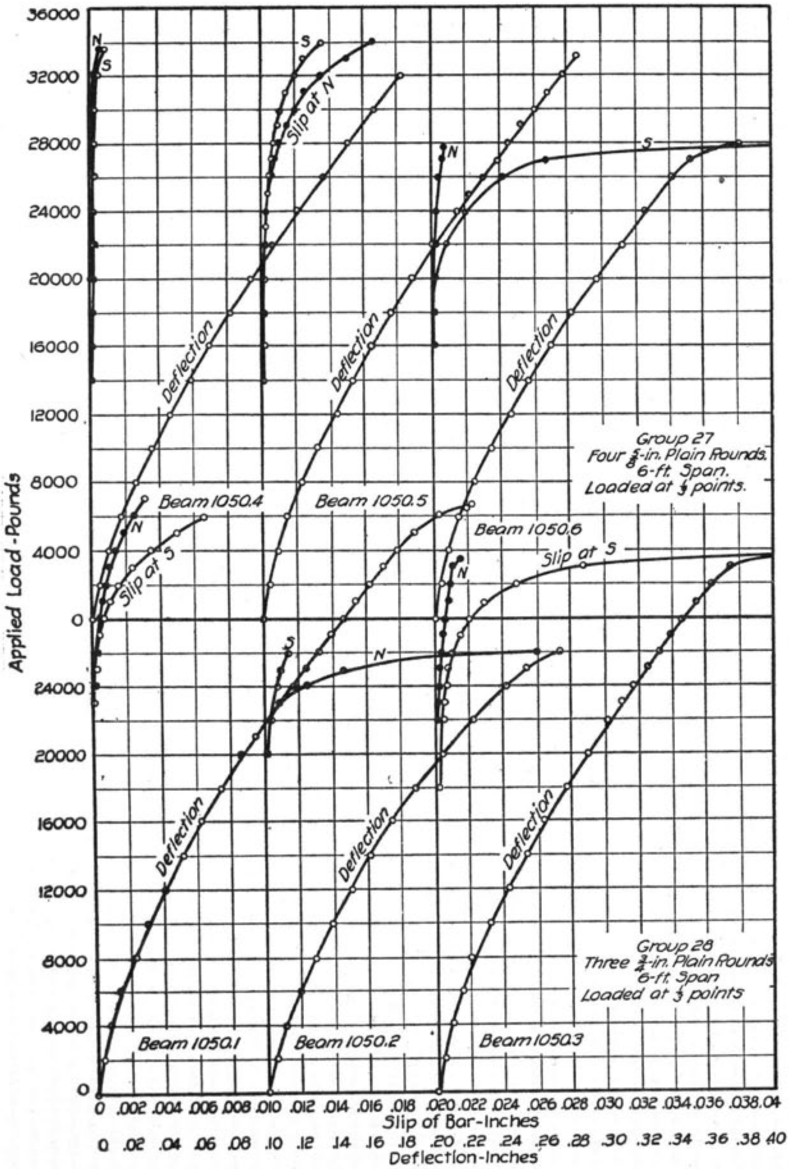

FIG. 84. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

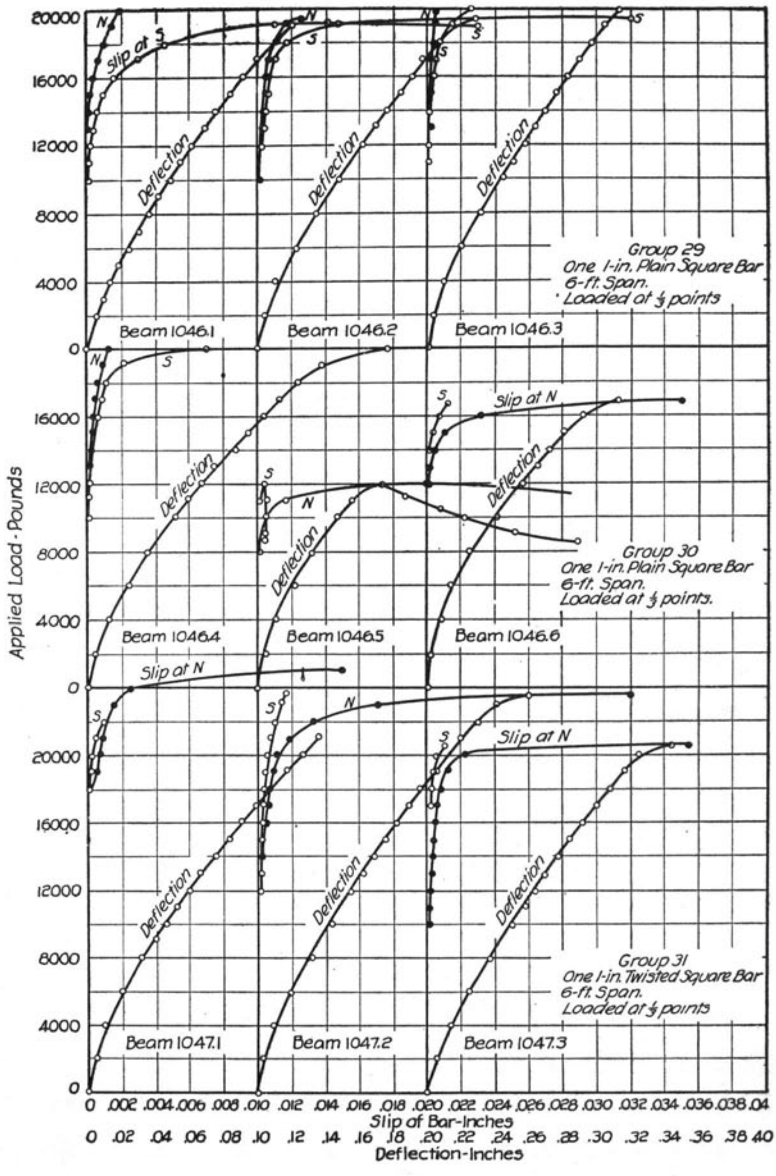

FIG. 85. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

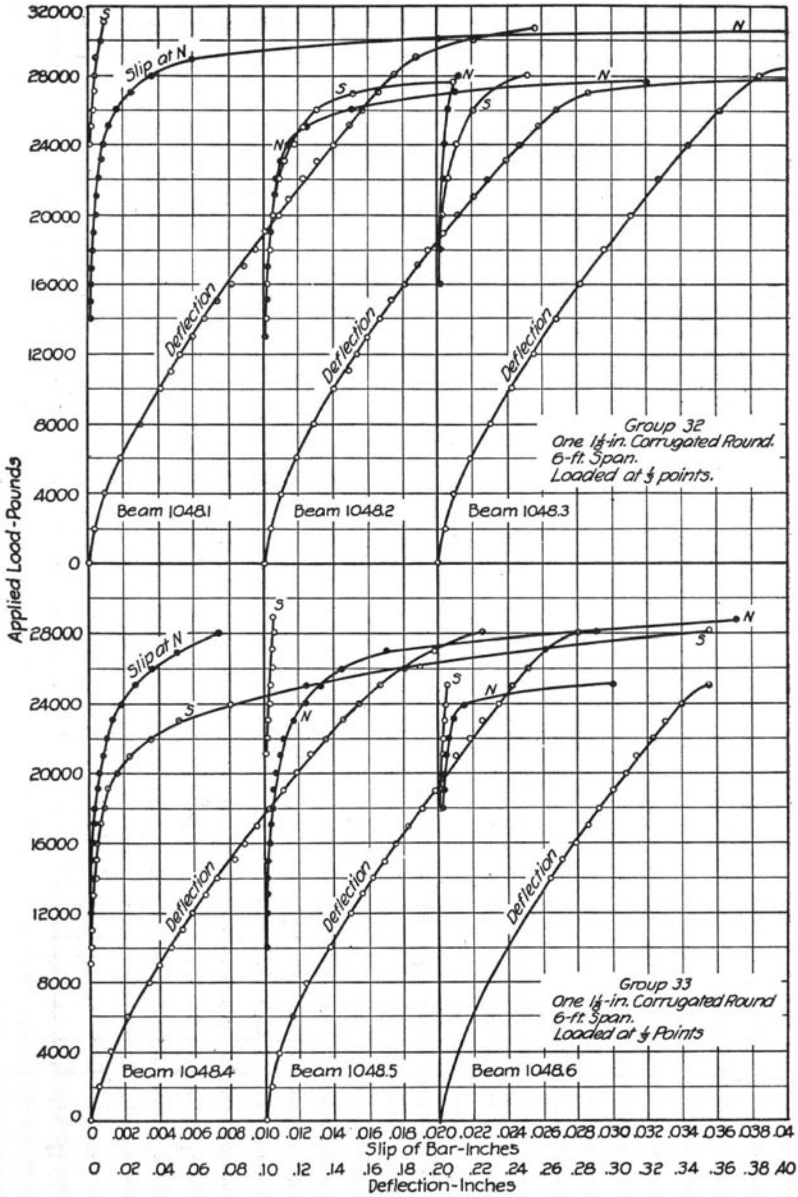

FIG. 86. LOAD-DEFLECTION AND END-SLIP CURVES FOR REINFORCED CONCRETE BEAMS.

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